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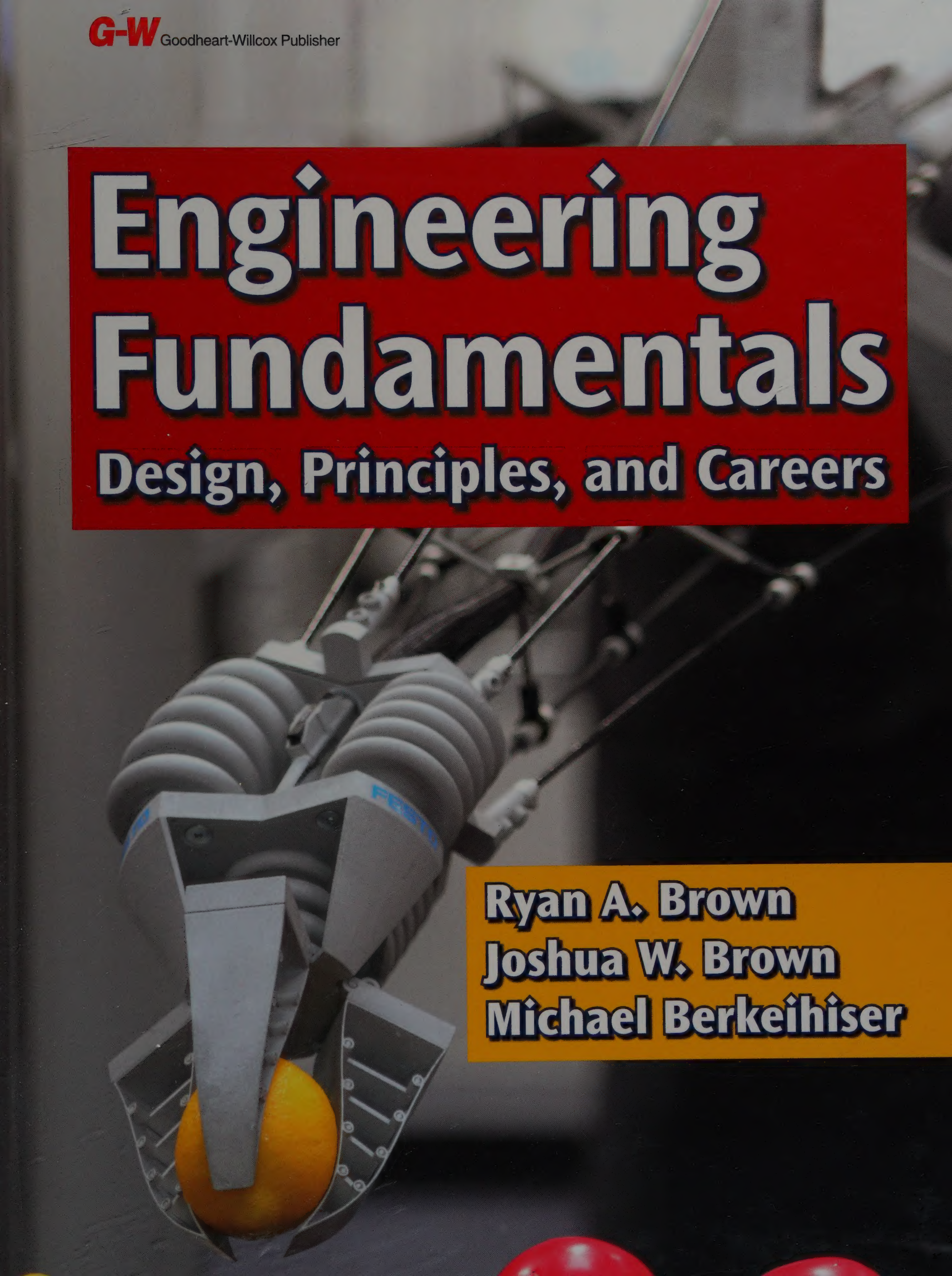
Engineering Fundamentals

Design, Principles, and Careers



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Engineering Fundamentals

Design, Principles, and Careers

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Introduction

What is engineering? *Engineering Fundamentals* provides a complete introduction to the field. It is written to help you learn about engineering and how it affects our everyday lives. You will learn how engineering is different from science and technology. You will also learn how science, math, and technology are an integral part of engineering design.

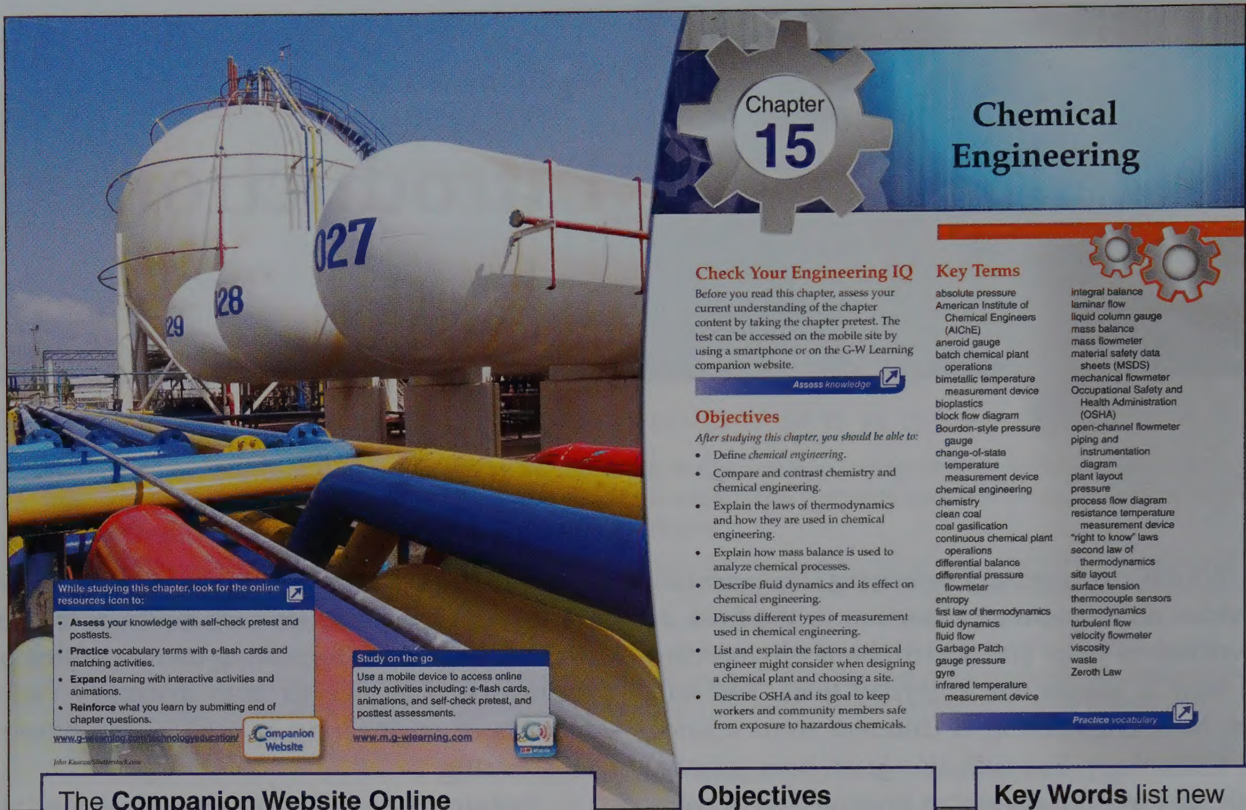
Engineering Fundamentals begins by giving you a clear picture of the basics of engineering. First, you will learn about engineering and the types of work engineers in various disciplines do. You will then read an extensive, five-chapter introduction to the engineering design process. Real-world examples are given to help you understand why each step of the process is necessary when designing new products, devices, or systems.

This section is followed by nine chapters that focus on engineering disciplines. Each of these chapters describes the specific engineering career, its educational requirements, and examples of real-world engineering projects. *Engineering Fundamentals* also discusses the principles associated with each discipline. The basic science and math required to understand the engineering and technology principles are explained in these chapters.

The final chapter discusses engineering as a profession. This includes such topics as the functions of engineers, regulating bodies, ethics, and teamwork. The chapter also discusses various impacts of engineering as well as the future of engineering.

Engineering Fundamentals is illustrated with photographs and drawings to help explain chapter concepts. Each chapter begins with a list of objectives. Important terms related to engineering are shown in ***bold italics*** where they are defined. Test Your Knowledge questions at the end of each chapter help check your understanding of chapter material. Several features throughout the chapter enhance chapter content while explaining related math, science, history, tools, or green concepts.

Engineering Fundamentals will educate you about career opportunities in engineering and provide practical applications of math and science principles. *Engineering Fundamentals* will inspire you to consider engineering-related careers and to be more successful in your math and science courses.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- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 15

Chemical Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *chemical engineering*.
- Compare and contrast chemistry and chemical engineering.
- Explain the laws of thermodynamics and how they are used in chemical engineering.
- Explain how mass balance is used to analyze chemical processes.
- Describe fluid dynamics and its effect on chemical engineering.
- Discuss different types of measurement used in chemical engineering.
- List and explain the factors a chemical engineer might consider when designing a chemical plant and choosing a site.
- Describe OSHA and its goal to keep workers and community members safe from exposure to hazardous chemicals.

Key Terms

absolute pressure
American Institute of Chemical Engineers (AIChE)
aneroid gauge
batch chemical plant operations
bimetallic temperature measurement device
bioplastics
block flow diagram
Bourdon-style pressure gauge
change-of-state temperature measurement device
chemical engineering
chemistry
clean coal
coal gasification
continuous chemical plant operations
differential balance
differential pressure flowmeter
entropy
first law of thermodynamics
fluid dynamics
fluid flow
Garbage Patch
gauge pressure
gyre
infrared temperature measurement device
integral balance
laminar flow
liquid column gauge
mass balance
mass flowmeter
material safety data sheets (MSDS)
mechanical flowmeter
Occupational Safety and Health Administration (OSHA)
open-channel flowmeter
piping and instrumentation diagram
plant layout
pressure
process flow diagram
resistance temperature measurement device
"right to know" laws
second law of thermodynamics
site layout
surface tension
thermocouple sensors
thermodynamics
turbulent flow
velocity flowmeter
viscosity
waste
Zeroth Law

Practice vocabulary

The **Companion Website Online Resources Icon** is shown throughout the text to lead students to additional materials.

Objectives identify the topics covered and goals to be achieved by students.

Key Words list new vocabulary covered in the chapter, enhancing student recognition of important concepts.


Chapter 1 What Is Engineering? 9

Science

Science in Engineering

Engineering includes the use of science to create products and systems that improve the world. There are several diverse areas of science, so what kinds of science are used in engineering? Science can be defined as the branch of study dealing with the knowledge of facts. Different areas of science study different areas of facts.

Earth science, for example, examines different facts relating to nature. This includes knowledge of minerals (used in materials engineering) and soil characteristics (used in manufacturing engineering).

Chemistry is focused on how matter is composed. Understanding such concepts as atoms, elements, and compounds is necessary for materials engineers as well as chemical engineers.

Biology is the study of living things. Bioengineers and biomedical engineers must have knowledge of biological concepts in order to design and improve products and systems in their field. Knowledge of cells, genetics, and body systems is essential for bioengineers and biomedical engineers to do their work.

Physics is an area of science that focuses on matter and energy and their relationship. Physics can be found in various engineering disciplines as well. For example, laws of gravity are necessary for aerospace engineering. Laws of conservation are used in both electrical engineering and aerospace engineering. Potential energy and kinetic energy are scientific concepts necessary for several fields of engineering, including mechanical engineering.

Some engineering fields require the knowledge of multiple areas of science. These scientific principles are discussed throughout this text.

Engineering technicians are people who carry out much of the technical work of an engineer. They generally use more technology and less scientific and mathematical knowledge than engineers. They may complete tasks such as drafting, computer modeling, troubleshooting, materials testing, technical writing, and surveying. Engineering technicians have either a two- or four-year degree in engineering technology. They often specialize in an engineering discipline and work with engineers in the same discipline. For example, an aerospace engineering technician would work with an aerospace engineer.

Tradespeople are workers who build the design solutions. They follow the plans that have been created by the engineer and put on paper by the engineering technician. For example, a mechanical engineer who has designed a new gearbox would use a tradesperson, such as a CNC operator or machinist, to build the physical part. See Figure 1-8. Tradespeople have specific technical knowledge and skills in material processing or construction.

Figure 1-8. Craftspeople, such as this welder, help build engineered products.

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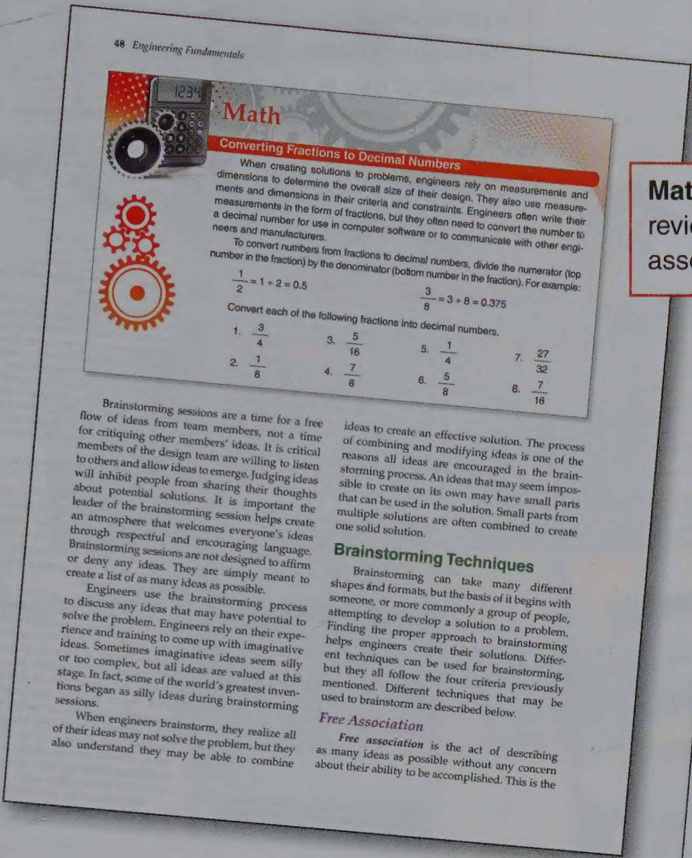
Science features review basic science concepts related to chapter material.

New Terms appear in bold italics where they are defined.



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Math

Converting Fractions to Decimal Numbers

When creating solutions to problems, engineers rely on measurements and dimensions to determine the overall size of their design. They also use measurements and dimensions in their criteria and constraints. Engineers often write their measurements in the form of fractions, but they often need to convert the number to a decimal number for use in computer software or to communicate with other engineers and manufacturers.

To convert numbers from fractions to decimal numbers, divide the numerator (top number in the fraction) by the denominator (bottom number in the fraction). For example:

$\frac{1}{2} = 1 \div 2 = 0.5$ $\frac{3}{8} = 3 \div 8 = 0.375$

Convert each of the following fractions into decimal numbers.

1. $\frac{3}{4}$
2. $\frac{1}{8}$
3. $\frac{5}{16}$
4. $\frac{7}{8}$
5. $\frac{1}{4}$
6. $\frac{5}{8}$
7. $\frac{27}{32}$
8. $\frac{7}{16}$

Brainstorming sessions are a time for a free flow of ideas from team members, not a time for critiquing other members' ideas. It is critical members of the design team are willing to listen to others and allow ideas to emerge. Judging ideas will inhibit people from sharing their thoughts about potential solutions. It is important the leader of the brainstorming session helps create an atmosphere that welcomes everyone's ideas through respectful and encouraging language. Brainstorming sessions are not designed to affirm or deny any ideas. They are simply meant to create a list of as many ideas as possible.

Engineers use the brainstorming process to discuss any ideas that may have potential to solve the problem. Engineers rely on their experience and training to come up with imaginative ideas. Sometimes imaginative ideas seem silly or too complex, but all ideas are valued at this stage. In fact, some of the world's greatest inventions began as silly ideas during brainstorming sessions.

When engineers brainstorm, they realize all of their ideas may not solve the problem, but they also understand they may be able to combine ideas to create an effective solution. The process of combining and modifying ideas is one of the reasons all ideas are encouraged in the brainstorming process. An ideas that may seem impossible to create on its own may have small parts that can be used in the solution. Small parts from multiple solutions are often combined to create one solid solution.

Brainstorming Techniques

Brainstorming can take many different shapes and formats, but the basis of it begins with someone, or more commonly a group of people, attempting to develop a solution to a problem. Finding the proper approach to brainstorming helps engineers create their solutions. Different techniques can be used for brainstorming, but they all follow the four criteria previously mentioned. Different techniques that may be used to brainstorm are described below.

Free Association

Free association is the act of describing as many ideas as possible without any concern about their ability to be accomplished. This is the

Math features give students a review of basic math concepts associated with chapter content.

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Figure 11-9. Everyday waste items, such as food and lawn care waste, can be used to make compost for the home.

Going Green

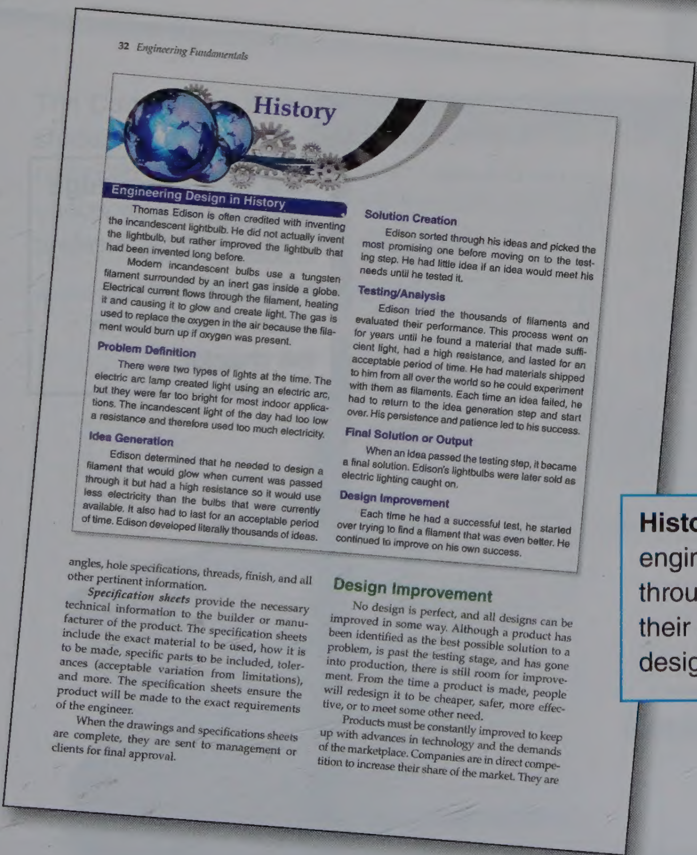
Vertical Farms

The world population continues to grow. In 1800, the world had a population of 978 million people. In 1900, the world population was 1.6 billion people. The current population is about 7 billion people. It is anticipated that by the year 2050, the world population will have increased to over 9 billion people. As a society, we must be able to produce enough food to feed the world population. Through more efficient farming and improved biotechnologies, we have been able to adapt to the growing population, and we will need to continue to adapt in the future.

One idea, proposed by Dr. Dickson Despommier, a professor at Columbia University in New York City, is to create vertical farms. Vertical farms are designed to grow *up* instead of *out*. They could be used in urban areas with very little land and would be built high in the air like a skyscraper. The vertical farm would need to have irrigation, lighting, and a method of processing the fruits and vegetables. Also, the vertical farm would need to be environmentally friendly, safe, cheap to build and maintain, and easily adaptable to different types of produce. See **Figure A**.

Figure A.

Going Green features explore the ways in which engineers are striving to make their designs more environmentally friendly.



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History

Engineering Design in History

Thomas Edison is often credited with inventing the incandescent lightbulb. He did not actually invent the lightbulb, but rather improved the lightbulb that had been invented long before.

Modern incandescent bulbs use a tungsten filament surrounded by an inert gas inside a globe. Electrical current flows through the filament, heating it and causing it to glow and create light. The gas is used to replace the oxygen in the air because the filament would burn up if oxygen was present.

Problem Definition

There were two types of lights at the time. The electric arc lamp created light using an electric arc, but they were far too bright for most indoor applications. The incandescent light of the day had too low a resistance and therefore used too much electricity.

Idea Generation

Edison determined that he needed to design a filament that would glow when current was passed through it but had a high resistance so it would use less electricity than the bulbs that were currently available. It also had to last for an acceptable period of time. Edison developed literally thousands of ideas.

Solution Creation

Edison sorted through his ideas and picked the most promising one before moving on to the testing step. He had little idea if an idea would meet his needs until he tested it.

Testing/Analysis

Edison tried the thousands of filaments and evaluated their performance. This process went on for years until he found a material that made sufficient light, had a high resistance, and lasted for an acceptable period of time. He had materials shipped to him from all over the world so he could experiment with them as filaments. Each time an idea failed, he had to return to the idea generation step and start over. His persistence and patience led to his success.

Final Solution or Output

When an idea passed the testing step, it became a final solution. Edison's lightbulbs were later sold as electric lighting caught on.

Design Improvement

Each time he had a successful test, he started over trying to find a filament that was even better. He continued to improve on his own success.

angles, hole specifications, threads, finish, and all other pertinent information.

Specification sheets provide the necessary technical information to the builder or manufacturer of the product. The specification sheets include the exact material to be used, how it is to be made, specific parts to be included, tolerances (acceptable variation from limitations), and more. The specification sheets ensure the product will be made to the exact requirements of the engineer.

When the drawings and specifications sheets are complete, they are sent to management or clients for final approval.

Design Improvement

No design is perfect, and all designs can be improved in some way. Although a product has been identified as the best possible solution to a problem, is past the testing stage, and has gone into production, there is still room for improvement. From the time a product is made, people will redesign it to be cheaper, safer, more effective, or to meet some other need.

Products must be constantly improved to keep up with advances in technology and the demands of the marketplace. Companies are in direct competition to increase their share of the market. They are

History features further explore engineers and their designs throughout history, explaining how their knowledge has led to today's designs.

Tools features detail the types of tools that are used in a particular area of engineering, as well as how to use them safely and effectively.

Design features showcase a particular element of the engineering design process and explain its role in the final solution.

Chapter 6 Modeling, Testing, and Final Outputs 93

Understanding the symbols is critical for mathematical modeling. In Bernoulli's principle, the *v* stands for the fluid speed, *g* is the acceleration of fluid due to gravity, *z* is the elevation point, *p* is the pressure and ρ is the density of the fluid.

Common mathematical formulas used by engineers from different disciplines are included in later chapters of this text.

Physical Modeling

Physical models are 3-D replicas of the final design of a solution. Models are used to illustrate the design, test the design, or experiment with materials. Physical models usually fall into two categories: mock-ups and prototypes.

A ***mock-up*** is a physical model that is used to show the design of an object. Mock-ups are built at full size or scaled to decrease or increase the size of the object to make it easier to view. Mock-ups are primarily used to demonstrate the object to others, to illustrate particular features of an object, or to evaluate the design. Designs progress from a paper drawing to a mock-up because engineers want to learn about how the product will look when it is created. Mock-ups are also used to obtain feedback from other people involved in the design project. Mock-ups are usually created with less expensive material than the final design. Mock-ups may use any material, but mock-ups are normally created with paper, cardboard, or foamboard to simulate the appearance of the final product. See **Figure 6-3**.

Tools

3-D Printers

One tool used to create models of objects is 3-D printers. 3-D printers use plastic placed in layers to create a model of an object. A 3-D printer "prints" by creating these layers.

Engineers design an object in a CAD software program. When they print their design, they send the file to a 3-D printer. The 3-D printer heats plastic and layers the plastic to create the object.

Technology has changed dramatically in the 3-D printing industry over the last 20 years. Machines have reduced and price and can now be used by consumers at home.

Figure 6-3. Mock-ups show what a final design will look like, though the materials used in a mock-up are only intended to simulate the appearance.

Chapter 13 Aerospace Engineering 265

Design

Flight Simulators

The word *simulation* is used to describe the imitation of something. Flight simulators imitate aspects of flight and are used to train pilots and design, test, and evaluate all aspects of flight in a safe and cost-effective way.

The most basic computer simulators involve desktop computers. Users interact with the computer to get a very general idea of such jobs as an air traffic controller or a pilot. The most advanced simulators include exact replicas of the cockpit of the craft a pilot is testing or learning to fly. High-definition screens show the pilots exactly what they would see out their windows if they were flying. The simulators are mounted on hydraulic jacks that move the entire cockpit to simulate what it would feel like to fly a particular craft.

Simulators can be used to test and evaluate the designs of aircraft parts and entire aircraft that have not yet been built. Software shows how the designs will perform. This saves time and money that would be required to build aircraft and helps remove the danger of flying completely untested aircraft.

As you know, engineers can go back to a previous step in the design process or even start over if their designs fail to meet their goals in testing. Simulation offers a much faster and less expensive evaluation process before design solutions are physically built.

Bernoulli theory of lift relies on the Bernoulli principle that an increase in fluid speed creates a decrease in pressure. See **Figure 13-5**. An airfoil is curved more on the top so that the air traveling over the wing has to travel farther than the air traveling under the wing. This causes the air flowing over the wing to flow faster relative to the wing than the air flowing under the wing, causing a low pressure zone above the wing and, therefore, lift. There is an area of lower pressure above most wing designs, but it does not completely explain lift.

Newtonian theory is based on Newton's third law of motion and the idea of a skipping stone. If you skip a stone across the water, the water pressure on the bottom of the stone keeps the stone on top of the water as long as there is sufficient velocity. Newtonian theory is based on the idea that air particles hit the bottom of the airfoil and are deflected downward. This downward deflection of the air causes the wing to be lifted upward. **Figure 13-6** describes Newton's third law and its effect on lift. The flaw in this theory is that it assumes the top of the airfoil has no effect on lift. It has been proven that both the top and the bottom affect lift.

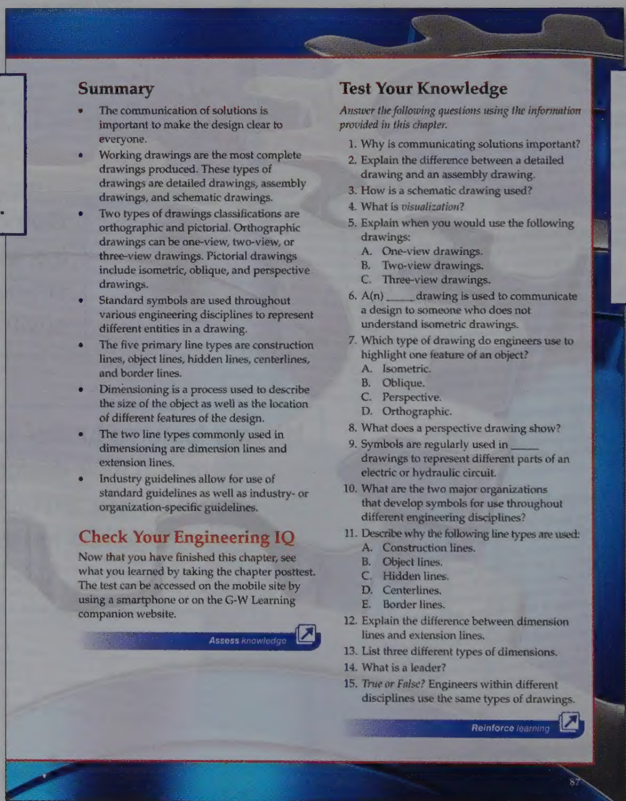
Regardless of the theory, it is known that the entire wing works together to create lift. Speed is an important consideration when calculating lift.

Airfoil

Figure 13-5. The air over this wing moves faster and creates low pressure.

NASA

Summary provides the student a review of major concepts covered in the chapter.



Summary

- The communication of solutions is important to make the design clear to everyone.
- Working drawings are the most complete drawings produced. These types of drawings are detailed drawings, assembly drawings, and schematic drawings.
- Two types of drawings classifications are orthographic and pictorial. Orthographic drawings can be one-view, two-view, or three-view drawings. Pictorial drawings include isometric, oblique, and perspective drawings.
- Standard symbols are used throughout various engineering disciplines to represent different entities in a drawing.
- The five primary line types are construction lines, object lines, hidden lines, centerlines, and border lines.
- Dimensioning is a process used to describe the size of the object as well as the location of different features of the design.
- The two line types commonly used in dimensioning are dimension lines and extension lines.
- Industry guidelines allow for use of standard guidelines as well as industry- or organization-specific guidelines.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. Why is communicating solutions important?
2. Explain the difference between a detailed drawing and an assembly drawing.
3. How is a schematic drawing used?
4. What is *visualization*?
5. Explain when you would use the following drawings:
   A. One-view drawings.
   B. Two-view drawings.
   C. Three-view drawings.
6. A(n) _____ drawing is used to communicate a design to someone who does not understand isometric drawings.
7. Which type of drawing do engineers use to highlight one feature of an object?
   A. Isometric.
   B. Oblique.
   C. Perspective.
   D. Orthographic.
8. What does a perspective drawing show?
9. Symbols are regularly used in _____ drawings to represent different parts of an electric or hydraulic circuit.
10. What are the two major organizations that develop symbols for use throughout different engineering disciplines?
11. Describe why the following line types are used:
    A. Construction lines.
    B. Object lines.
    C. Hidden lines.
    D. Centerlines.
    E. Border lines.
12. Explain the difference between dimension lines and extension lines.
13. List three different types of dimensions.
14. What is a leader?
15. *True or False?* Engineers within different disciplines use the same types of drawings.

Reinforce learning

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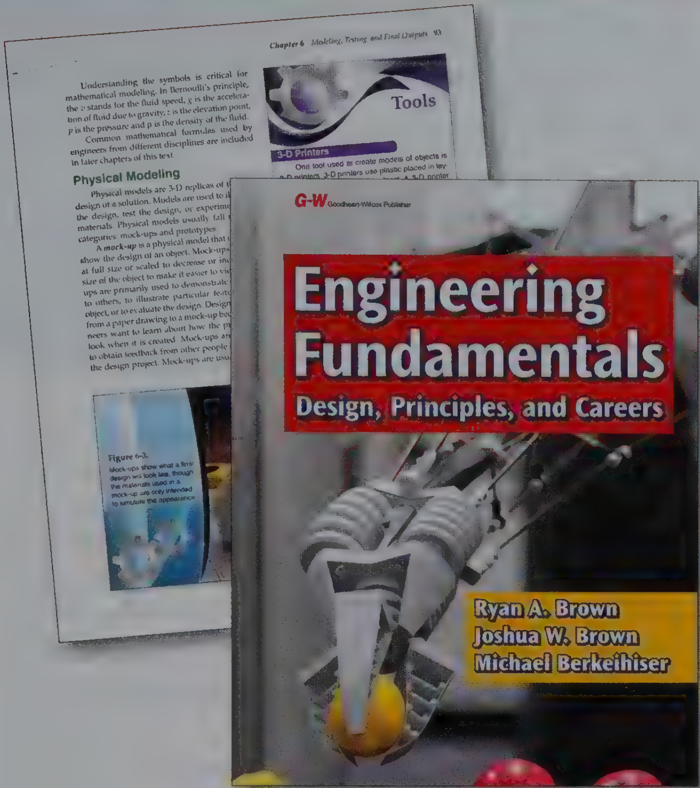
Test Your Knowledge questions help students review the topics and the material covered in the chapter.



The **Student Textbook** of *Engineering Fundamentals* is available as a printed textbook or as an interactive online text.

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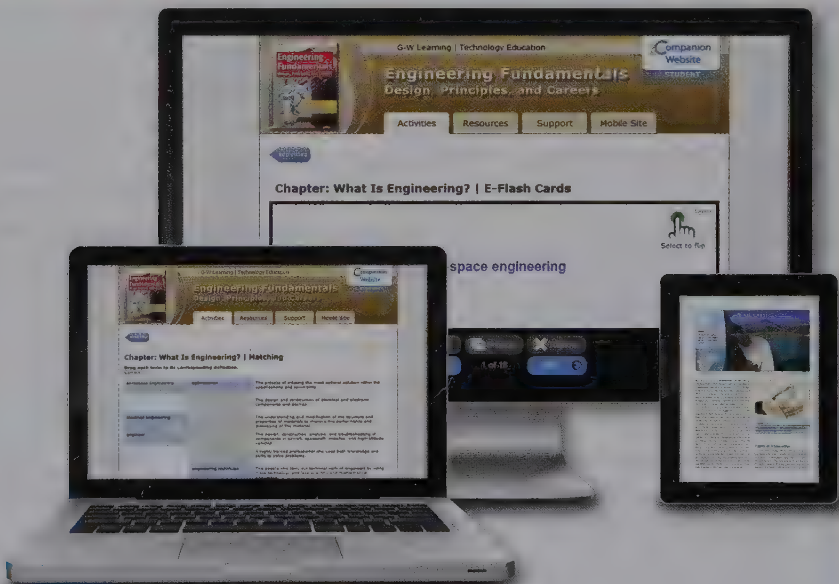

The **Companion Website** provides students with the opportunity to increase comprehension and retention of key concepts. Includes vocabulary practice, pretests, posttests, and animations.

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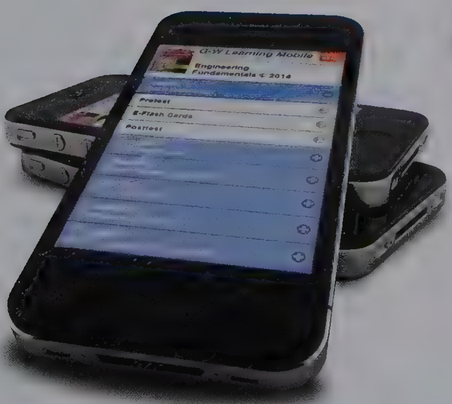

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Michael Berkeihiser has written numerous journal articles for Technology and Engineering Teacher and the TEEAP Journal and has presented at many conferences. Berkeihiser has also coauthored *Manufacturing and Automation Technology* with Dr. R. Thomas Wright. Berkeihiser teaches Engineering Design, Architectural Design, and Electronics at Unionville High School in Kennett Square, Pennsylvania. Unionville's Technology Education Department won ITEA and TEEAP Program Excellence Award in 2009. Berkeihiser's educational background includes a bachelor's degree from Millersville University and a master's degree from Ball State University.

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Chapter 1

What Is Engineering?

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- Define *engineering*.
- Identify and describe the types of knowledge used by engineers.
- List the roles that make an engineering team.
- List several engineering disciplines.
- Summarize the historical developments in engineering.

Key Terms

aerospace engineering
bioengineering
chemical engineering
civil engineering
computer engineering
constraints
electrical engineering
engineer
engineering
engineering design process
engineering technician
manufacturing engineering
materials engineering
mechanical engineering
optimization
specifications
trade-off
tradespeople

Practice *vocabulary*

Have you ever thought that it would be exciting to be an engineer? You may have thought that it would be interesting to build bridges, design automobiles, or develop computer software. These are just three examples of the thousands of products and systems that engineers design. You come in contact with the products of engineers every day, maybe without even realizing it. Engineers formed the layout and construction of the roads that you take to school. The cell phone that you use to communicate was designed by an engineer. The medicines that you use were manufactured under the oversight of an engineer. And the electricity that powers your school and home was made possible by the work of engineers. It is hard to find an aspect of our lives that are not impacted by the world of engineering and the work of engineers. See **Figure 1-1**.

Engineering Defined

What then is engineering and what do engineers do? ***Engineering*** is the use of mathematics, science, and technology to create products and systems that improve the world. ***Engineers*** are highly trained professionals who use both knowledge and skills to solve problems. To solve problems, engineers combine their knowledge of math and science with the use of materials and natural forces. For example, engineers use mathematical and scientific principles to harness moving water in the creation of hydroelectric dams. See **Figure 1-2**. Other engineers use mathematical and scientific principles related to electricity and materials to design and create computer processors, which can provide computing power to everything from handheld devices to large Internet servers.

Problem Solving

Engineers approach the problems they are given (usually from employers, clients, or government agencies) in a very specific manner. Engineers use an engineering design process to design and create solutions to problems. The ***engineering design process*** is a specific set of steps that lead the engineer from a problem statement to a final solution. The process is purposeful rather than based on trial-and-error. Engineers do not happen upon a solution or "twiddle" with something until they fix the problem. The engineering design process is explained in detail in later chapters.

Throughout the solving of a design problem, engineers are faced with many decisions. The decisions must take into account several design parameters. The first set of decisions is

Figure 1-1.
This engineer oversees the construction on a jobsite.

Sandra Gligorijevic/Shutterstock.com

Figure 1-2.
Hydroelectric dams are one of the largest modern engineering projects.

Ronald Sumners/Shutterstock.com

the specifications. ***Specifications*** are the design requirements. The second set is constraints. ***Constraints*** are the limitations of the design. Common constraints are materials, costs, size, and time. For example, a biomedical engineer creating a prosthetic hand must know how the hand is supposed to function (specifications). The engineer must also know what materials can be used, how much it can cost, and the weight that it cannot exceed (constraints). See **Figure 1-3**. The role of the engineer is then to create the most optimal solution while balancing the specifications with the constraints. The optimal solution may be to create a product at a maximum profit per unit, or a product with the greatest range of motion at the least weight per unit. In reality, it is often very difficult to meet all of the specifications while staying within the constraints. ***Optimization*** is the process of creating the most optimal solution within the specifications and constraints. A ***trade-off*** is something an engineer gives up in order to meet other specifications while staying within the constraints. In the above example, the engineer may find that it is impossible to design the prosthetic hand at an appropriate weight that functions as desired. As engineers decide which is most important (function or weight), they are making a trade-off.

Figure 1-3.
The specifications for this prosthetic hand include that its grip is precise enough to pick up a die.

Touch Bionics

Types of Knowledge

Engineers make design decisions, including trade-offs, based on the design parameters and their mathematical, scientific, and technical knowledge. This knowledge is gained both through coursework while pursuing engineering degrees and from professional work experience.

The knowledge used in each engineering field is slightly different and specialized, but all engineers rely on mathematical, scientific, and technical knowledge. See **Figure 1-4**.

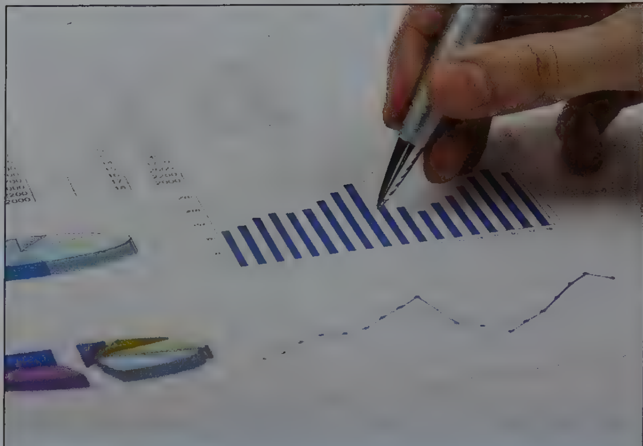

Figure 1-5.

Engineers rely on graphs and charts to make decisions.

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Mathematical Knowledge

Much of the work that engineers do requires the analysis of data. Engineers spend a considerable amount of time reviewing graphs, charts, and data tables to either understand the problem or to determine the appropriateness of their design. See **Figure 1-5**. This type of work requires a strong background in various types of mathematics. Algebra may be used to determine the relationship between two variables in a system, like temperature and time. Or civil engineers may use math to determine the amount of beam deflection as they design a bridge. When engineers are concerned with rate of change in an object or forces acting on an object, they use calculus principles. The use of statistics and statistical models is also a common use of mathematics in engineering. Engineers may use statistics to perform failure analyses, to ensure reliability, or to justify design decisions.

Scientific Knowledge

Engineering is often referred to as the practical application of science. So, engineers must have a strong understanding of science in order to apply its principles. The scientific knowledge that is needed varies depending on the field of engineering. Civil and architectural engineers need to understand scientific concepts such as statics, force, load, and tension. Electrical engineers need to understand principles such as Ohm's law, atomic structure, and circuit theory. Other scientific principles that relate to engineering include thermodynamics, kinematics, fluid mechanics, and Boolean logic. These topics are introduced in later chapters.

Technical Knowledge

The work of engineers often requires the use technical knowledge in the form of the use of tools. Engineers use design technology such as computer-aided design software, drawing tools, and simulation software. See **Figure 1-6**. Engineers may also use tools such as gauges, meters,

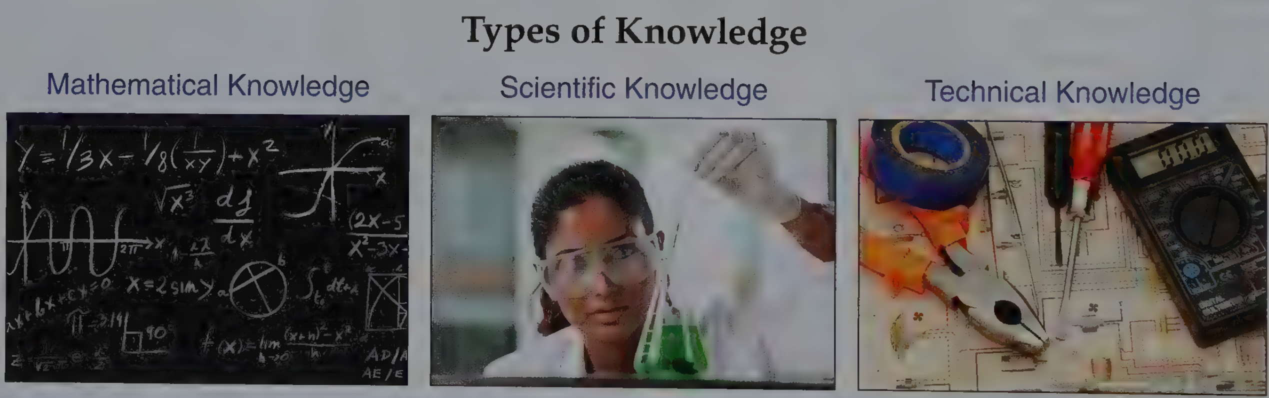

Figure 1-4.

To solve design problems, engineers need mathematical knowledge, scientific knowledge, and technical knowledge.

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Math

Applying Math (Units of Measure)

Mathematics is an integral part of engineering, as much of an engineer's time is spent making calculations. The calculations have two parts: a numerical value and a unit. The system of units that has been adopted globally by most engineering communities is the *Système International d'unités* (International System of Units), known as the SI system. Common SI units are meters, kilograms, and liters. However, not all engineers use SI units. The standard system of units in the United States is the US customary system. Common units in this system are inches, feet, pounds, and quarts. Conversion charts like the one below are useful when converting from one system of units to another:

Measurements	SI Units	US Units	From SI to US	From US to SI
Length	meter (m)	foot (ft)	1 m = 3.281 ft	1 ft = 0.305 m
Mass	kilogram (kg)	pound (lb)	1 kg = 2.205 lb	1 lb = 0.454 kg
Volume	liter (L)	quart (qt)	1 L = 1.057 qt	1 qt = 0.946 L
Area	square centimeter (cm^2)	square inch (in^2)	1 cm^2 = 0.155 in^2	1 in^2 = 6.452 cm^2

To convert units using this chart, multiply the numerical value with the number in the chart. For example, to convert 5 meters into feet, multiply 5×3.281, which equals 16.405 ft.

Convert each of the following numbers and units.

1. 6 ft to meters
2. 15 kg to pounds
3. 4 qt to liters
4. 20 cm^2 to square inches
5. 3 m to feet
6. 21 lb to kilograms
7. 7 L to quarts
8. 15 in^2 to square centimeters

scales, and statistical software as they design, implement, and operate solutions to problems. Lastly, engineers use a range of communication tools from e-mail to document preparation and presentation software.

Types of Skills and Traits

Engineers not only need specific knowledge but also a certain set of skills and traits. Engineers must enjoy and be good at solving problems. Engineers must be able to see problems and then break them into smaller parts in order to solve the larger problem. This is similar to solving puzzles. People who are detail oriented and analytical are well suited for engineering. Creativity is also an important trait for an engineer. Problem solving often requires creative approaches and solutions. Drawing and design skills are important for engineers.

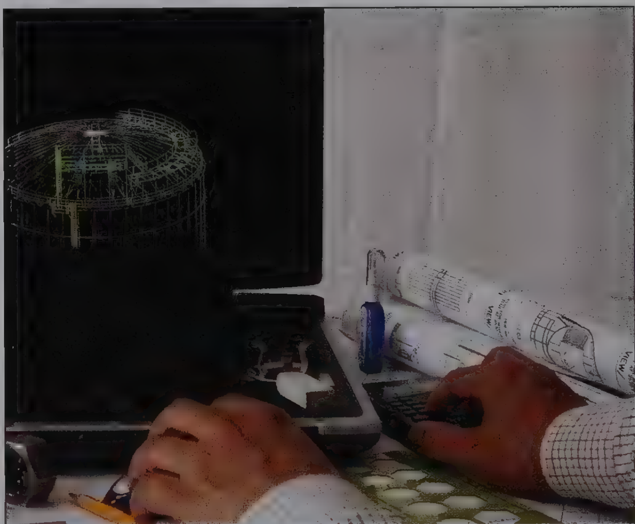

Figure 1-6.

Many types of engineers use computer software to design products.

RAGMA IMAGES/Shutterstock.com

Engineers must have good interpersonal skills. These skills include being able to maintain positive relationships with coworkers, being a good team member, and expressing your feelings appropriately through good communication skills. See **Figure 1-7**.

Communication skills are important because engineers work with many other people. Engineers must be able to plan and give effective presentations. Being a good listener also falls under communication skills. Strong written communication skills are also needed because much of an engineer's time will be spent writing technical reports, memos, and e-mails.

Lastly, time management and project management skills are necessary. The schedule and number of projects that an engineer may be working on at any given time may be demanding.

Role of Engineers

Engineered projects require the work of many people. Not everyone involved in an engineered project is an engineer. Many roles must be fulfilled in order for a project to move from a problem statement to an engineered solution. Let's use the example of a design and building of a skyscraper. Engineers would focus on a number of different aspects of the design and construction. Structural engineers are hired to design the building so it is safe and uses materials efficiently. Architectural engineers design the electrical, plumbing, and heating systems in the skyscraper. Civil and construction engineers oversee the construction of the project. Systems engineers coordinate and manage the entire project from beginning to end.

Each stage of the project, however, requires more than just engineers. Engineers generally work with teams of people. The teams may include other engineers, but could also include engineering technicians and tradespeople. Each person on the team has a specific role in the design, creation, and operation of an engineering project.

Engineers are the lead designers or analysts in an engineering project. They keep the "big picture" in mind. Their role is to find a solution to the design problem while keeping the specifications and constraints in mind. Engineers also coordinate the entire process and make the final design decisions. Engineers often approach design problems using scientific and mathematical theory. Engineers must have at least a bachelor's degree in engineering or an engineering specialty, but many have advanced graduate degrees.

Figure 1-7.
Engineers often work in teams. Teamwork relies on good communication and interpersonal skills.

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Science in Engineering

Engineering includes the use of science to create products and systems that improve the world. There are several diverse areas of science, so what kinds of science are used in engineering? Science can be defined as the branch of study dealing with the knowledge of facts. Different areas of science study different areas of facts.

Earth science, for example, examines different facts relating to nature. This includes knowledge of minerals (used in materials engineering) and soil characteristics (used in manufacturing engineering).

Chemistry is focused on how matter is composed. Understanding such concepts as atoms, elements, and compounds is necessary for materials engineers as well as chemical engineers.

Biology is the study of living things. Bioengineers and biomedical engineers must have knowledge of biological concepts in order to design and improve products and systems in their field. Knowledge of cells, genetics, and body systems is essential for bioengineers and biomedical engineers to do their work.

Physics is an area of science that focuses on matter and energy and their relationship. Physics can be found in various engineering disciplines as well. For example, laws of gravity are necessary for aerospace engineering. Laws of conservation are used in both electrical engineering and aerospace engineering. Potential energy and kinetic energy are scientific concepts necessary for several fields of engineering, including mechanical engineering.

Some engineering fields require the knowledge of multiple areas of science. These scientific principles are discussed throughout this text.

Engineering technicians are people who carry out much of the technical work of an engineer. They generally use more technology and less scientific and mathematical knowledge than engineers. They may complete tasks such as drafting, computer modeling, troubleshooting, materials testing, technical writing, and surveying. Engineering technicians have either a two- or four-year degree in engineering technology. They often specialize in an engineering discipline and work with engineers in the same discipline. For example, an aerospace engineering technician would work with an aerospace engineer.

Tradespeople are workers who build the design solutions. They follow the plans that have been created by the engineer and put on paper by the engineering technician. For example, a mechanical engineer who has designed a new gearbox would use a tradesperson, such as a CNC operator or machinist, to build the physical part. See **Figure 1-8**. Tradespeople have specific technical knowledge and skills in material processing or construction.

Figure 1-8.

Craftspeople, such as this welder, help build engineered products.

Sukharevskyy Dmytro (nevodka)/Shutterstock.com

Welders, CNC operators, electricians, machinists, and installers are all examples of craftspeople. Tradespeople may have associate degrees or may have participated in an apprenticeship program.

Each role—engineer, engineering technician, and tradesperson—is extremely important in the development of engineered products, systems, and structures. For example, the tradesperson relies on the engineer for the design, and the engineer relies on the tradesperson for the technical skill. Each role has a specific set of skills required to do the job. For people who like to work with their hands and to follow plans and drawings, the job of a tradesperson may be a great fit. For those who enjoy math and science, are creative, and enjoy designing things, the role of an engineer may be a better fit. For others that fall somewhere between the two, the job of an engineering technician may be the right position.

Engineering Disciplines

Engineers, engineering technicians, and tradespeople work in a number of different engineering disciplines. Today's prospective engineer starts by choosing a discipline to study. That selection, or specialization, determines the type of engineer the student becomes. Today, a number of disciplines and subdisciplines exist. Several of the more common fields of engineering are presented here and are explained in more detail later in this text. These fields include materials engineering, electrical engineering, civil engineering, mechanical engineering, biotechnical engineering, computer engineering, aerospace engineering, manufacturing engineering, and chemical engineering.

Materials Engineering

Materials engineering focuses on designing and testing new materials and finding new ways to use existing materials. Engineers in all fields need to know a great deal about materials and their uses, but materials engineers understand the nature of materials at a deeper level. Materials engineers often focus on a specific type of material such as metals, plastics, ceramics, or composites. See **Figure 1-9**. Materials engineers may be employed to develop a specific material for a specific application, such as designing a material that would be strong enough to withstand the impacts that a mountain bike takes, but still be light enough to be feasible for use in a bike. Materials engineers may design materials

Figure 1-9.
Many products today are manufactured using new materials, such as carbon fiber.

dutourdumonde/ Shutterstock.com

for use in prosthetics. They may design materials to be easily recyclable, or they may even design a new alloy for a specific application. Materials engineers must understand material properties such as atomic structure, strength, stress, strain, and elasticity. These principles and others are described in Chapter 7.

Electrical Engineering

Electrical engineering is one of the widest fields of engineering, in terms of the products that are designed. Electrical engineers design and develop electrical and electronic systems and products. Electrical engineers work on projects as large as power generation stations to devices as small as handheld consumer electronics. A number of electrical engineers design electrical systems for vehicles such as hybrid automobiles, aircraft, and spacecraft. See **Figure 1-10**. Other electrical engineers are employed in the telecommunications industry developing satellite systems, in the energy sector working on alternative power systems, and in the medical field designing new devices and instruments. The wide use of electricity and electronic devices has led to a range of areas of specialization within electrical engineering. Electrical engineers must understand and be able to apply principles such as the nature of electricity; voltage, current, and resistance; circuit design; and electrical measurement. These principles and others are described in Chapter 8.

Figure 1-10.

NASA scientists troubleshoot an instrument to be placed on the *Global Hawk* designed to measure atmospheric conditions.

NASA

Civil Engineering

Civil engineering is concerned with both the structures that we build and the use and control of natural resources, especially water. Civil engineering is considered the oldest of the engineering fields as its principles have been used for thousands of years. Civil engineers plan and coordinate large-scale construction projects such as airports, highway systems, and municipal water and sewage systems. Structural engineering is one of the largest subfields in civil engineering. Structural engineers spend their time studying how forces interact within a structure. The structure may be a building, a bridge, a tunnel, or even the *International Space Station*. Civil engineers may also be employed by a company to design solutions for solid waste removal or by a city to design a water treatment plant or city water system. Civil engineers study concepts such as statics, mechanics, surveying and mapping, and the use of different construction materials. Civil engineering is the focus of Chapter 9.

Mechanical Engineering

Mechanical engineering is the designing, building, and maintaining of mechanical, thermal, and fluid systems. These systems include products such as tools and machines; engines and turbines; heating, cooling, and refrigeration systems; vehicles; and household products and devices. Each of the previous systems is a potential specialty area for mechanical engineers. Mechanical engineers are employed by automakers to design engines, by manufacturing facilities to design and control robotic devices, and by power generation companies to design and maintain devices that generate electricity.

Other mechanical engineers design machine tools that are used to build other machines. Mechanical engineers must understand concepts such as mechanics, pneumatics, hydraulics, power transmission, gear ratios, and efficiency. These principles and others are described in Chapter 10.

Bioengineering

Bioengineering is the use of engineering concepts to attend to problems relating to biology. Two subfields of bioengineering are biomedical engineering and agricultural engineering. The two are often linked because they both deal with biological problems; biomedical engineers focus on humans, and agricultural engineers focus on plants and animals. Biomedical engineers design devices such as artificial organs, prosthetics, and medical imaging systems. These engineers may be called on to design new devices for use in surgeries or new medical diagnostic tools. Agricultural engineering is the application of engineering concepts to issues related to the food supply. Agricultural engineers design machines, processes, and products for all aspects of farming. This could include farm machinery, biofuels and fertilizers, farming processes such as hydroponics, and even devices and processes for soil and water management. See **Figure 1-11**. Bioengineering is the focus of Chapter 11.

Computer Engineering

Computer engineering is the design, development, and testing of various aspects of computer systems. This could include computer hardware and peripherals, computer software, and computer network devices. Computer engineers develop or improve operating systems by creating innovative ways for the computer hardware to interact with the software or with the user. They may also help to design devices that use computer chips such as toys, smart devices, or even industrial robots. Computer engineers are continuously working to improve computer performance and to find ways to fully utilize computer capabilities. A subfield of computer engineering is software engineering. Software engineers design computer applications while computer engineers focus more on the hardware and operating systems. Computer engineers must understand concepts such as computer logic, computer architecture, and human-computer interaction. These principles and several applications of computer engineering are discussed in Chapter 12.

Figure 1-11.
This example of bioengineering shows how a biofuel refinery produces ethanol from corn crops.

AZP Worldwide/Shutterstock.com

Aerospace Engineering

Aerospace engineering is the design, testing, and manufacturing of air and space vehicles. Aerospace engineers design, build, analyze, and troubleshoot components of aircraft, spacecraft, missiles, and space planes. Aerospace engineering is divided into two main categories. Aeronautics is the design of aircraft, and astronautics deals with the design of spacecraft. See **Figure 1-12**. Aerospace engineers are often employed by large commercial aviation companies such as Boeing and Lockheed Martin or by government organizations such as the Department of Defense or the National Aeronautics and Space Administration (NASA). However, as commercial space travel has become more of a reality, smaller aerospace companies are hiring aerospace engineers. Aerospace engineers study concepts such as fluid dynamics, aerodynamics, principles of flight, and aircraft and spacecraft design. The principles and applications of aerospace engineering can be found in Chapter 13.

Manufacturing Engineering

Manufacturing engineering is the design and coordination of all aspects of the production of products. Manufacturing engineers design assembly lines. They organize material handling processes and supervise the quality control of manufacturing processes. They focus on producing products in the most efficient ways possible. Manufacturing engineers examine current production facilities to find ways to cut costs, reduce downtime of machines, better utilize workers, and improve the flow of goods. They work in all industries that manufacture products. Manufacturing engineers must understand material processes, plant and process layout, principles of quality control, and material handling techniques. These principles and applications of manufacturing engineering are discussed in Chapter 14.

Chemical Engineering

Chemical engineering is concerned mainly with the large-scale production of chemicals and chemical products. Many chemical engineers are employed in the petroleum, pharmaceutical, and food processing industries. Other chemical engineers may work with plastics, paper, food additives, sustainable energy products, synthetic materials, biomedical products, and cosmetics. They often design new production techniques, aid in the design of chemical manufacturing

Figure 1-12.
This rocket is the result of the work of aerospace engineers.

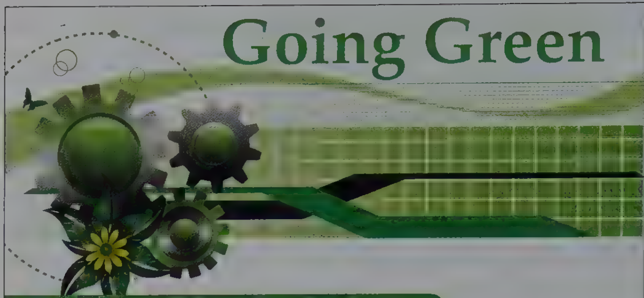
NASA

facilities, and work to improve the safety of such facilities. See **Figure 1-13**. Chemical engineers use their technical and scientific knowledge to solve problems dealing with chemicals, other materials, and large-scale production. Chemical engineering principles and applications are the focus of Chapter 15.

Other Engineering Disciplines

The engineering disciplines discussed in the previous sections (and in more depth later in this text) are examples of the largest disciplines. However, there are a number of additional engineering disciplines that create valuable products and solve important problems. Environmental engineers, for example, design environmentally friendly products and work to improve air and soil quality. Nuclear engineers design ways to safely use nuclear materials as power sources. Petroleum and mining engineers find new ways to extract raw materials from the earth that are safe and economical.

All processes and products that are developed, improved, and tested have been influenced by engineers at some point in their development. Engineering, as a whole, covers a wide spectrum of fields and has developed over time.



Environmental Engineering

While all engineers think about the impact they make on the environment, one group of engineers makes it their focus. Environmental engineers work to improve and protect the environment and enhance human health. Environmental engineers work in a number of areas including air pollution control, hazardous waste management, wastewater management, and public health. Environmental engineers may be employed by companies to design ways to lessen their air and water pollution, or by environmental groups as consultants, or by the government as environmental regulators. Other environmental engineers may work in foreign countries to help open access to natural resources, such as clean water. As the world becomes more conscious of the environmental impacts of our technical society, people such as environmental engineers will be in greater demand. Their knowledge will be needed to find new ways to reduce pollution and make the environment safer for those living in it.

Figure 1-13. Modern chemical facilities are designed and maintained by chemical engineers.

Light & Magic Photography/Shutterstock.com

History of Engineering

Engineering has been an activity that humans have been involved with for thousands of years. Engineering as a defined profession is only several hundred years old, but the engineering of buildings and structures dates back to 2000 BCE. See **Figure 1-14**. The builders of these structures would resemble civil engineers today. However, not all fields of engineering can be traced back thousands of years. Consider computer engineering. As a discipline of study, it is only about 50 years old. Therefore, each field of engineering has its own history and key developments. This brief history is meant only to provide an overview of several main historical developments in engineering.

Early Civilizations

The development of the field of engineering follows the development of human and societal needs. Humans began to engineer products, buildings, and structures as they needed water for farming, protection from other civilizations, and ways to honor their leaders. The Mesopotamians and Egyptians were the first civilizations to build structures that would have used engineering principles (especially mathematics). Over 5000 years ago, the Mesopotamians constructed temples and the Egyptians were able to construct massive pyramids to honor their rulers. See **Figure 1-15**. Around the same time, Egyptians had designed and built irrigations systems, dams, and aqueducts for the distribution of water for use in agriculture.

Several thousand years later in the first century BCE, the Romans not only built aqueducts to move water great distances, but also developed city water systems. The Romans also built an extensive system of roadways, some of which still exist some 2000 years later.

The engineering developments of the early civilizations were not confined only to civil engineering projects. The use and manufacture of metal tools and weapons can be found in many civilizations as early as 5000 years ago.

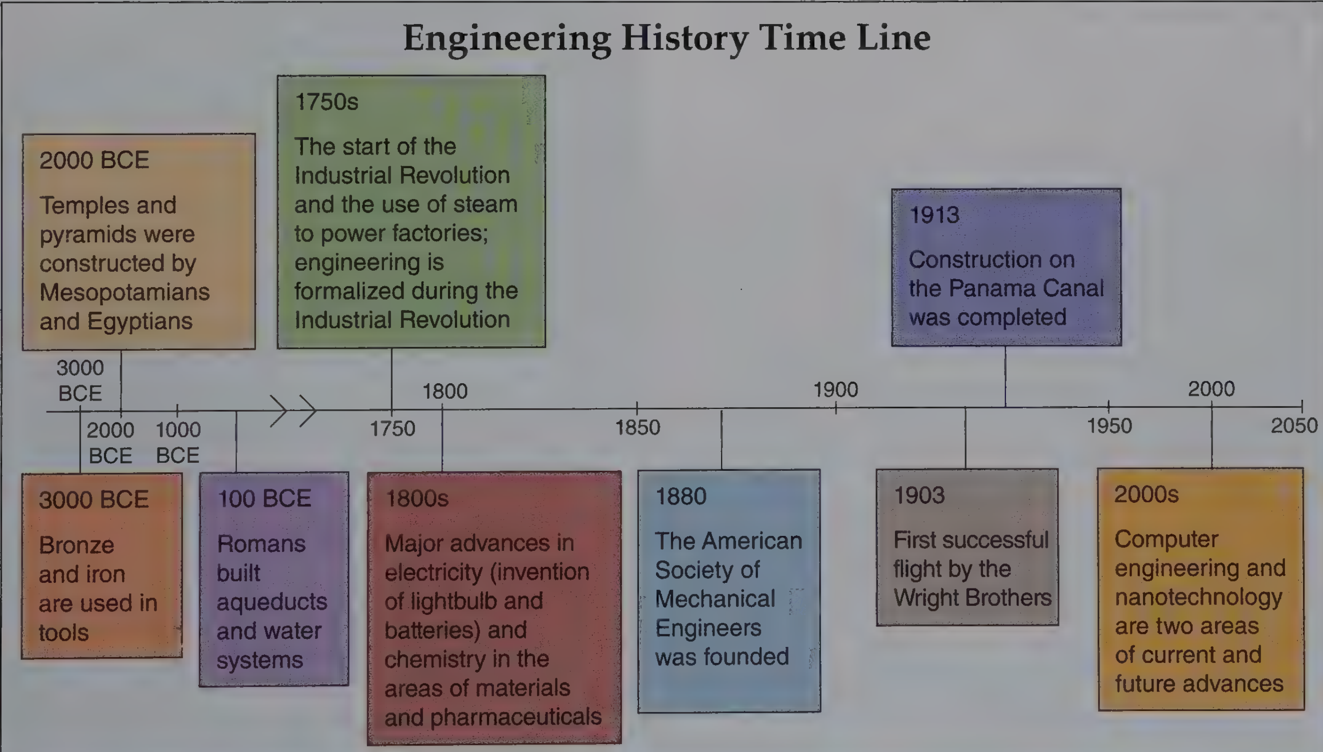


Figure 1-14.

This time line shows engineering through history.

Goodheart-Willcox Publisher

Figure 1-15.
The pyramids are examples of early engineered structures.

Pichugin Dmitry/Shutterstock.com

Bronze was the first metal to be used in tools, followed by iron. Vehicles, in the forms of carts, chariots, boats, and ships, were also created by these early civilizations. Mechanical devices, such as waterwheels, were used in ancient times by the Greeks, Romans, and Chinese. However, while these are certainly examples of technology, not all of the early structures, tools, and vehicles are considered engineered products. Many of these devices and structures were designed and built using a trial-and-error method rather than using mathematics and science as a foundation.

Industrial Revolution

The formalization of many forms of engineering can be found during the Industrial Revolution (1750–1900). During the Industrial Revolution, scientists, technologists, and engineers learned to harness scientific principles (many that were newly discovered) for use in mechanical and industrial devices. Many of the advancements were made possible by James Watt's improvements to the steam engine. This allowed the steam engine to be the main source of power for a range of devices. Steam engines transformed factories, as they became the main source of power for machines. See **Figure 1-16**. Steam engines made travel on rail possible through the development of the steam locomotives. The Industrial Revolution saw many advances in the area of mechanical engineering. In fact, the American Society of Mechanical Engineers (ASME) was founded in 1880, near the end of the Industrial Revolution.

Figure 1-16.
The development of the steam engine spurred advances in many industries, including transportation.

Richard Paul Kane/Shutterstock.com

Mechanical engineering, however, was not the only field of engineering to advance during the Industrial Revolution. Great advances in electricity and electrical engineering were made throughout the nineteenth century. Magnetic induction was

discovered by Michael Faraday and Alessandro Volta built the world's first battery at the beginning of the nineteenth century. By the end of the nineteenth century, Thomas Edison had invented an incandescent lightbulb and had built an electrical generation station in New York City. At the same time, Nikola Tesla invented the electric induction motor, and electrical engineering was beginning to be offered at American and European universities. Advances were also made in the scientific understanding of chemicals. During this time period, 70 of the 118 known chemical elements were discovered. This led to the engineering, development, and greater use of a number of new materials including vulcanized rubber, plastics, dynamite, artificial fertilizers, antiseptics, and other pharmaceuticals. The creation and mass production of these and other materials led to the growth of industrial chemistry, which would later become chemical engineering. Many advances were also made in agriculture and agricultural engineering throughout the Industrial Revolution. The cotton gin, the reaper, and the steel plow were all developed during the Industrial Revolution. Throughout the Industrial Revolution, new engineering degrees were being offered and colleges, universities, and numerous professional organizations were founded in several engineering disciplines. By the end of the Industrial Revolution and the nineteenth century, many aspects of the world were changing due to the work of engineers.

Twentieth Century Advances

Incredible engineering advances were made in the twentieth century. In civil and architectural engineering, buildings and structures reached new heights, massive engineering projects such as the Panama Canal were completed, and extensive highway systems were built. See **Figure 1-17**. Chemical engineers developed production facilities to produce and refine many of the products that we use today including plastics, pharmaceuticals, petroleum, paints, and food products. In the twentieth century, electrical engineers developed the radio, television, computer, electronics, satellite technology, and the infrastructure to support these technologies. Electrical engineering in the twentieth century also led to new branches of engineering including computer engineering, software engineering, and electronic engineering.

Figure 1-17.
The Panama Canal has been labeled as one of the grandest engineering projects in history. This image shows a ship moving through the lock.

Jim Lipschutz/Shutterstock.com

Aerospace engineering is another field of engineering that has been developed almost entirely in the twentieth century. While humans have dreamed of flight for thousands of years, it was not until the early 1900s that it became a reality. In the past 100 years, since the Wright Brothers' first flight, aeronautical engineering has enabled air travel to be a common part of our lives. Air travel and other aeronautical engineering advances have impacted recreational, commercial, and military aspects of our lives. The reality of flight and improvements in rocket science during World War II led to the twentieth century birth of aerospace engineering. In less than 75 years, aerospace engineers that started with the design of rockets have been able to land spacecraft on the moon and Mars, and have explored numerous parts of the solar system. Much of the ease of communication we enjoy today is a direct result of the satellite systems developed by aerospace and electrical engineers.

Many of the twentieth century advances in medicine, especially in medical imaging, have been made possible by biomedical engineers. See **Figure 1-18**.

Engineering in the Twenty-First Century

What will our world look like in the future? It is hard to say, but looking back at the accomplishments in various fields of engineering gives us an idea that the future will not be the same as the present. The future developments and advances will be the result of the work of engineers. Some advances will be easier than others to predict. Computer engineers will design computers that are more powerful, faster, and more capable; aerospace engineers will design vehicles that will make space travel more feasible and economical; mechanical engineers will design more efficient machines. Nanotechnology and the development and manipulation of products at a microscopic level will impact many areas of engineering. See **Figure 1-19**. However, engineers of the future will also design, build, and operate devices, structures, and systems that include technologies that are difficult to imagine today.

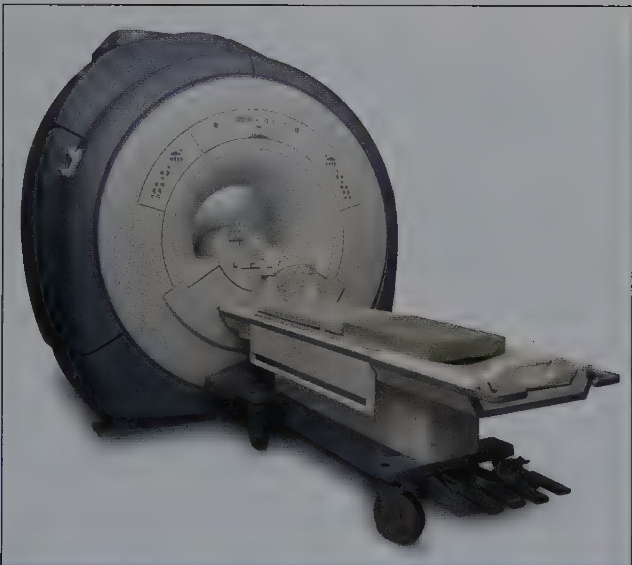


Figure 1-18.

This magnetic resonance imagining (MRI) machine is an example of advancement in biomedical engineering. MRI machines are used heavily in brain and cancer imaging.

James Steidl/Shutterstock.com

Figure 1-19.

This silicon wafer is one of many materials that is impacted by advances in nanotechnology.

chang, hui-ju/Shutterstock.com

Summary

- Engineering is the use of mathematics, science, and technology to create products and systems that improve the world. Engineering is a problem-solving and design process that is engaged in by engineers.
- Engineers use mathematical, scientific, and technical knowledge as well as a number of skills to solve engineering problems.
- Most engineered solutions require a team of skilled workers that may include engineers, engineering technicians, and craftspeople.
- The broad field of engineering is divided into a number of disciplines or fields. Several of those include electrical, civil, mechanical, and aerospace engineering.
- Each engineering discipline has a distinct history and will certainly impact the future.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

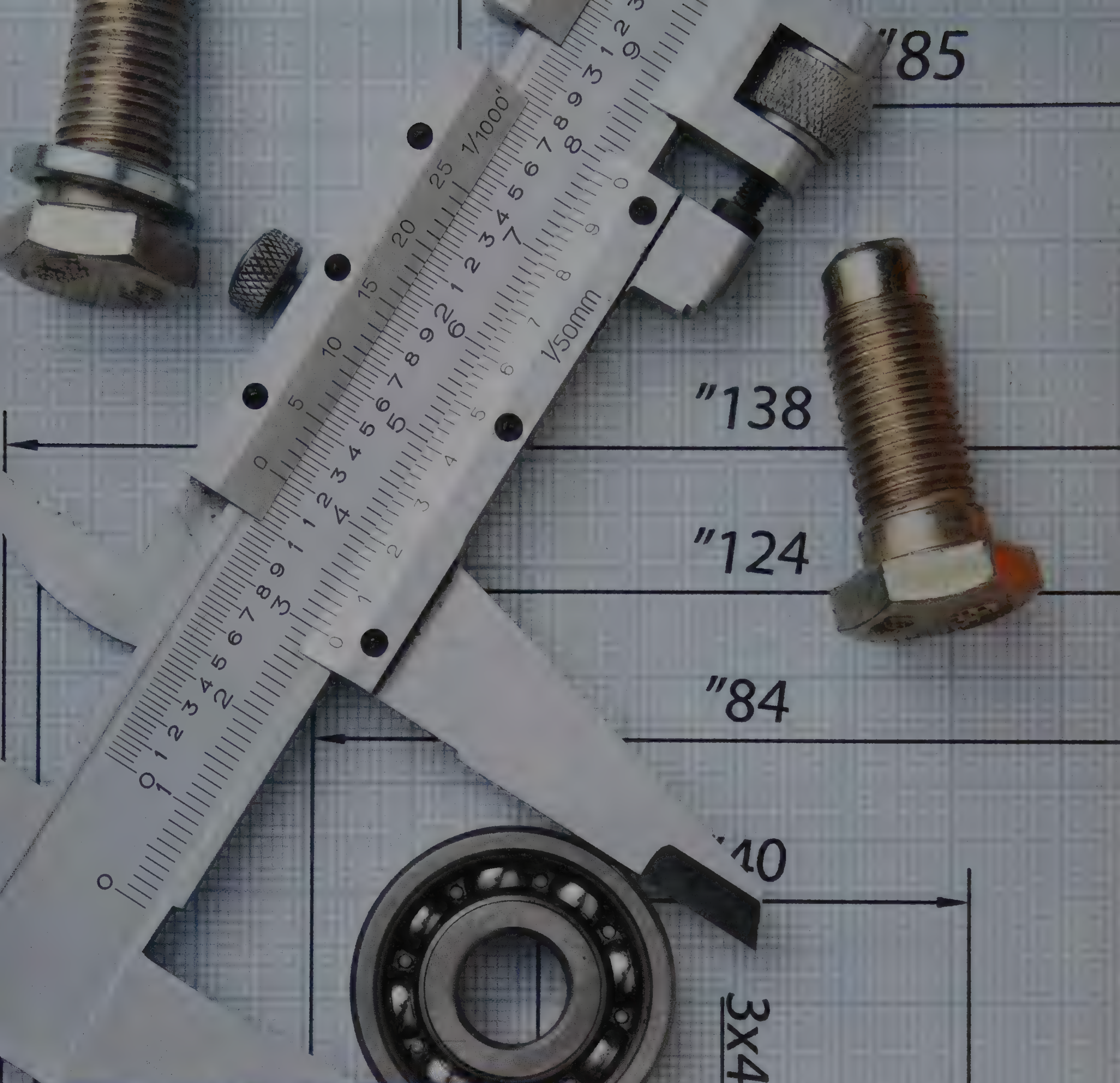
1. Define *engineering*.
2. Engineers use a(n) _____ process to solve problems.
3. The requirements of a design solution are known as _____.
4. List the three types of knowledge used by engineers.
5. List three skills or traits that are needed by engineers.
6. A(n) _____ is the lead designer in an engineering project.
7. The worker who builds the final solution is known as a(n) _____.
8. *True or False?* All fields of engineering have the same history and have developed in the same manner.
9. List two early civilizations that used engineering principles to build structures.
10. The _____ was a time period in which many forms of engineering were formalized.
11. List one field of engineering that was developed in the twentieth century.

Matching: Match the discipline of engineering with a typical project that is designed in that discipline.

12. Smart device
13. Tunnel
14. Factory plant layout
15. Alloy
16. Power generation station
17. Space plane
18. Machine tool
19. Pharmaceutical processing facility
20. Medical diagnostic tools

A. Electrical engineering
B. Civil engineering
C. Materials engineering
D. Mechanical engineering
E. Biotechnical engineering
F. Computer engineering
G. Aerospace engineering
H. Manufacturing engineering
I. Chemical engineering

Reinforce *learning*



While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

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Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 2

Engineering Design

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- Define *engineering design*.
- Describe the steps of the engineering design process.
- Explain how to define a problem and its constraints.
- Identify various methods of ideation.
- Summarize the processes of creating and testing design solutions.
- Explain how to communicate the final design solution.
- Describe the purpose of an engineering notebook.

Key Terms

brainstorming
computer simulation
computer-aided drafting (CAD)
computer numerical control (CNC)
design brief
detail drawing
engineering design
ideation
mechanical drawing
multiview drawing
orthographic drawing
pictorial drawing
problem statement
prototype
rapid prototyping
rendering
sketch
specification sheets
three-dimensional (3-D) model

Practice *vocabulary*

As you look around, everything you see that is human-made has been designed. The chair you are sitting in, the school you attend, and your favorite electronic device are all results of engineering design. Engineering design comes as a result of a need. Engineers do not invent needs; needs originate from society, and engineers design solutions that meet those needs. Think of the hybrid car. As fuel prices increase, worldwide oil deposits decrease, and we understand more about climate change, society has identified the need for a vehicle that could move people from one place to another while using the least possible fuel and, therefore, creating the least possible emissions. Hybrid cars were designed to use an electric motor and batteries to work with the gasoline engine. See **Figure 2-1**. The result is a highly efficient vehicle that uses much less fuel and creates far fewer emissions compared to conventional vehicles.

Engineering Design

Engineering design is the creative application of technology to design a system, product, or process to solve a given problem or meet a given need. Engineering design is very open-ended because there are often many solutions to problems rather than simply one correct answer. Engineering design involves finding not simply a solution, but the best possible solution given a specific problem and design criteria.

Engineering design is essential in all disciplines of engineering. Whether you plan to become a mechanical, electrical, aerospace, or other engineer, you will be called on to solve complex engineering design problems throughout your career. See **Figure 2-2**. To solve these types of problems, engineers must keep an open mind, maintain a positive attitude toward solving problems, be persistent, let the facts drive decisions, follow procedures, be creative and open to new ideas, and adhere to the engineering design process.

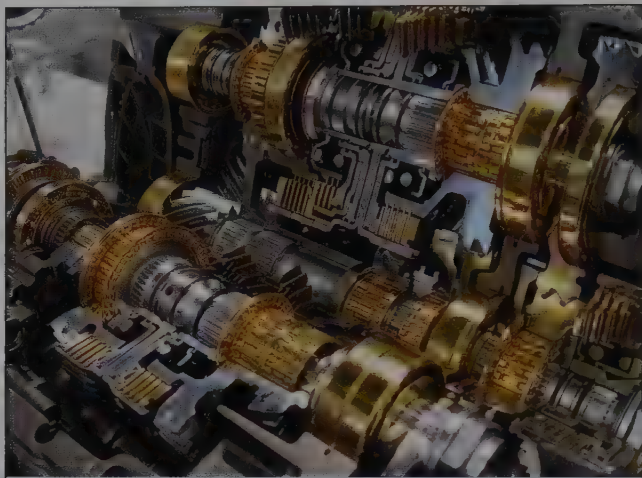

Figure 2-2.

The creation of this gearbox required an engineer to use the engineering design process.

yuyangc/Shutterstock.com

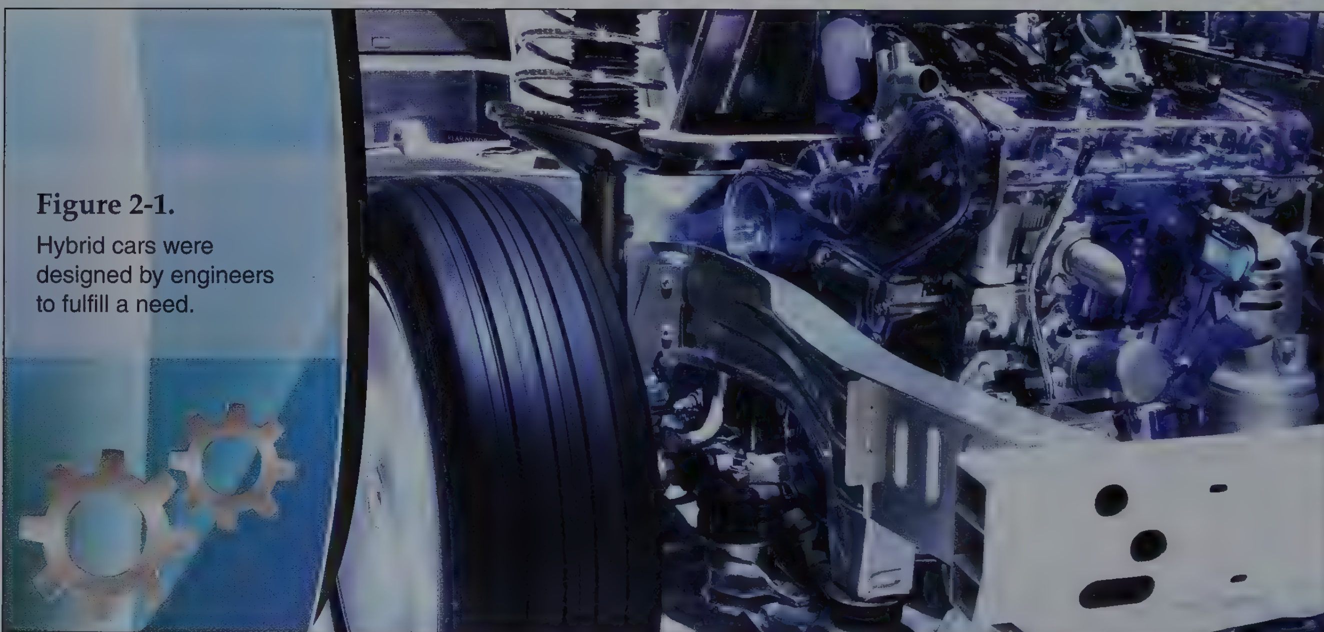

Figure 2-1.

Hybrid cars were designed by engineers to fulfill a need.

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Engineering Design Process

The engineering design process is a series of systematic steps that helps guide engineers from the identification of the problem to the best possible solution. Each step along the way is critical to ensure all information is taken into account and that all ideas are considered. Each engineer might choose to use his or her own specific steps, but all engineers use some sort of design process. A common engineering design process using six steps is shown in **Figure 2-3**. The six steps include problem definition, idea generation, solution creation, testing/analysis, final solution or output, and design improvement.

The engineering design process can be very linear as engineers work through the steps, but it will often require backtracking and repeating steps along the way because engineering design problems are often very open-ended and have many possible solutions. Engineers must follow the steps of the design process without skipping any, but they can go back and complete steps again if necessary. For example, if a design fails in the testing/analysis stage, it cannot continue through the process. The engineer will have to go back and generate new ideas and solutions. Sometimes information is uncovered during the design process that actually forces engineers to redefine the problem, requiring them to start over. In the final step, engineers can discover that there was a better way to solve the problem and they have to go back to a previous step.

The engineering design process can be used to solve a wide variety of problems, from creating a more fuel-efficient propulsion system for a space vehicle to helping you mange your homework and study time more efficiently so you can earn better grades in school. See **Figure 2-4**.

Figure 2-4.

The design process can be used in solving complex problems, but it can also be used to help you manage your homework more efficiently.

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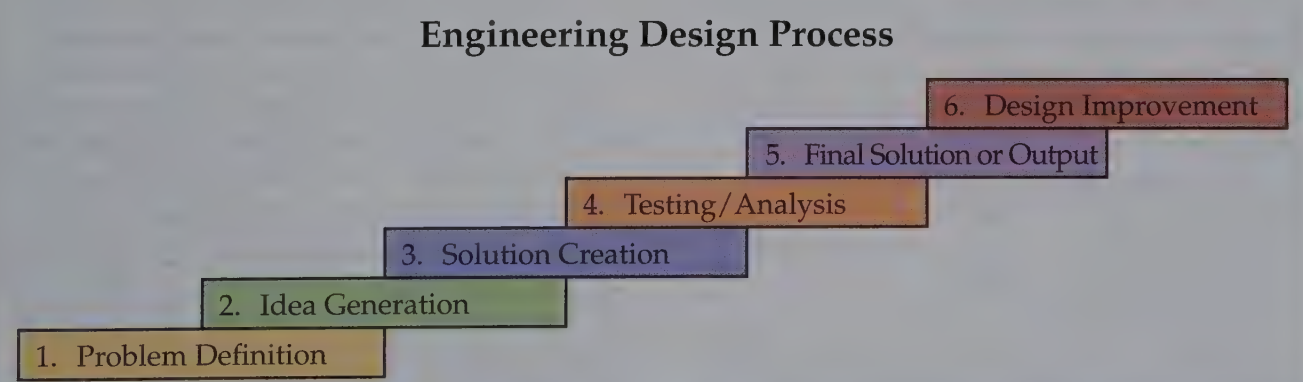

Figure 2-3

These six steps are common to the engineering design process.

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Problem Definition

Defining the problem can be the most important step in the design process. Once the real problem has been identified, the problem is well on its way to being solved. People often try to solve a symptom of the problem rather than the problem itself. It is important to get to the real problem. For example, imagine you bake cookies at home. You follow a recipe that says you should bake the cookies at 350° for 10 minutes, but the cookies keep burning to the cookie sheet. You go to the store and purchase a much more expensive cookie sheet with a thicker bottom that is advertised to cook more evenly, but the cookies continue to burn on the bottom. It turns out that the temperature gauge on your oven is not accurate, and you have been baking the cookies at 425° even though the gauge says 350°. In buying a new cookie sheet, you have solved the wrong problem. The real problem was that the temperature gauge was broken, and not that the cookie sheet was of low quality. Untold time and money is spent by design engineers who fail to properly identify the true problem before designing a solution.

In order to define the problem, engineers must do as much research and gather as much information as possible on the problem. Engineers must be willing and able to ask a lot of questions and look at problems from all angles. Engineers are often handed a problem by someone else. In industry, the problem, or need can be generated by market forces. A company may see an opportunity to make money selling a given product if it can be designed, built, and brought to market.

The Scientific Method

Similar to the engineering design process, the scientific method is a series of steps used to solve problems. However, because the goal of the scientific method is not to design or create solutions, the steps are different from those of the engineering design process. Similar to the engineering design process, a scientist may need to repeat steps in the process to achieve the desired results. The scientific method can be used to answer scientific questions as well as simple, everyday questions.

The following are the common steps of the scientific method:

1. Ask a question.
2. Research to form a hypothesis.
3. Experiment.
4. Gather and analyze data.
5. Form a conclusion.

The first step in the scientific method is typically to ask a question. Instead of defining a problem, you ask a question based on observation. As an example of an everyday problem, you observe the milk carton is stamped with today's date. Your question is, has the milk in your fridge gone bad?

The next step in the scientific method is to do research to form a hypothesis. A hypothesis is your prediction of the answer to your question. In this example, your research could be looking at the date on the carton or checking to see if the milk has a sour smell. Because the date on the milk carton is today and not yesterday, you predict that the milk is still good.

Once you have formed a hypothesis, you must experiment to discover whether your hypothesis is acceptable. Scientific experiments can be simple or complex. In our example, a simple experiment to test your hypothesis is to taste the milk. Your experiment will yield data, or information. Gathering and analyzing these data is the next step of the scientific method.

After you have experimented and have your data, you can form a conclusion. In the milk example, the experiment was to taste the milk. If the milk tastes good, your hypothesis was correct, and you can continue to drink the milk from the carton. If the milk tastes sour, your hypothesis was disproved, and you know to dispose of the bad milk.

The simple example of potentially bad milk shows the common steps of the scientific method.

Engineers are often called on to solve problems with equipment that breaks down or parts that fail. They could be called on to design new parts or systems to meet a given need. If the engineer was not the person who identified the problem, he or she should seek out the person who did identify the problem to make sure they understand the true problem.

The engineer must develop a problem statement. The ***problem statement*** outlines the problem in clear terms, but it is not so specific that it limits creativity in design. For example, a problem statement could be:

Student lockers fail to adequately meet the needs of students and custodial staff.

Problem Constraints

Once the problem has been identified and a problem statement has been written, it is time to define the constraints of the problem. Constraints are the limitations of the design, such as materials, costs, size, and time. Using our locker example, students report that their lockers are difficult and time consuming to lock and unlock, lack adequate ventilation, and do not allow for easy storage of common student materials. Custodians find the lockers difficult to clean. The outsides are cleaned weekly and the insides are completely cleaned out each summer. School administrators require that the lockers be upgraded on budget and occupy the same amount of floor space.

Lockers should be redesigned to meet the following needs:

- *Ample storage.*
- *Good airflow.*
- *Reasonable security.*
- *Convenient student use.*
- *Easy cleaning for custodians.*
- *Privacy.*
- *No floor space increase.*
- *Cost.*

The engineer creates a document called the ***design brief***, which guides the design process. See **Figure 2-5**. The design brief includes constraints, such as size, cost, and quality. These are the design requirements or constraints of the design. Understanding the constraints on the design is part of the problem definition stage. The constraints and background information must be fully understood before the engineer can move on to the idea generation stage.

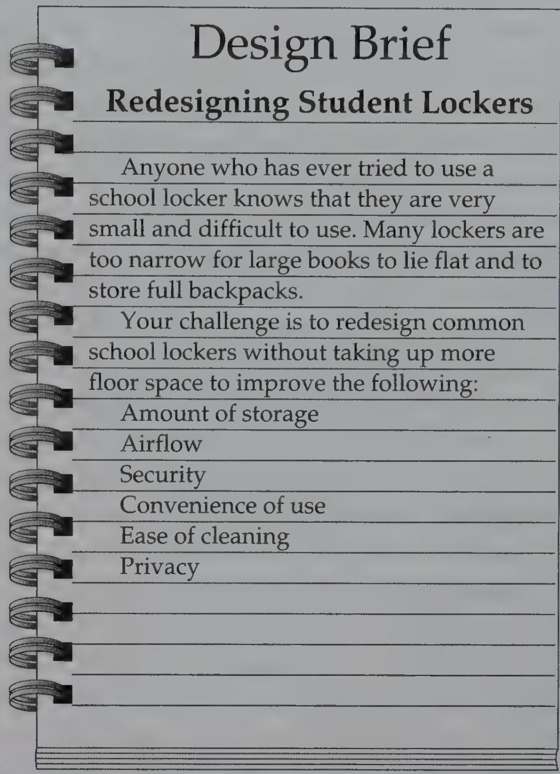

Figure 2-5.

The design brief guides the design process.

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Idea Generation

In the idea generation stage, engineers try to come up with as many different ideas, or solutions as possible without regard for evaluating them. The process of generating ideas is called ***ideation***. There are no wrong answers at this stage. The most important thing is to come up with as many ideas as possible. There is a direct link between the number of ideas generated at this stage and the quality of the final product of the design process. Generating a great idea starts with an open mind and the willingness to think outside the box. As more ideas are generated, a wide variety of solutions are available to the engineer in the next step. Increasing the number and variety of ideas increases the likelihood that one of them will be a good solution. Once a wide variety of ideas have been generated, each will be evaluated individually in the solution creation stage.

While there are numerous techniques for ideation, brainstorming is one of the most commonly used. ***Brainstorming*** involves generating ideas in order to develop solutions. This technique can be done by an individual, but is more commonly and more effectively done in groups. A group of people, preferably of diverse backgrounds, is brought together and given a problem. One person is selected to keep a record of ideas. Records are kept on a piece of paper, or they may be written on an easel or whiteboard so the whole group can see, **Figure 2-6**. Some ideas are recorded using words, and others require a simple sketch. The ideas are recorded so they can be examined and evaluated at a later time. The members of the group communicate any idea that comes to their minds without evaluating the idea at the time. Outlandish ideas and outside-the-box thinking are encouraged. There is no criticism or critique of any ideas at this stage because the goal is to get as many ideas as possible on paper and allow the team members to build on each other's ideas.

During the idea generation stage, record keeping is very important. Many ideas are brought up very quickly, and it is important that records be kept so ideas are not lost or forgotten. In engineering design, many of these ideas require drawings to adequately describe the concepts, **Figure 2-7**.

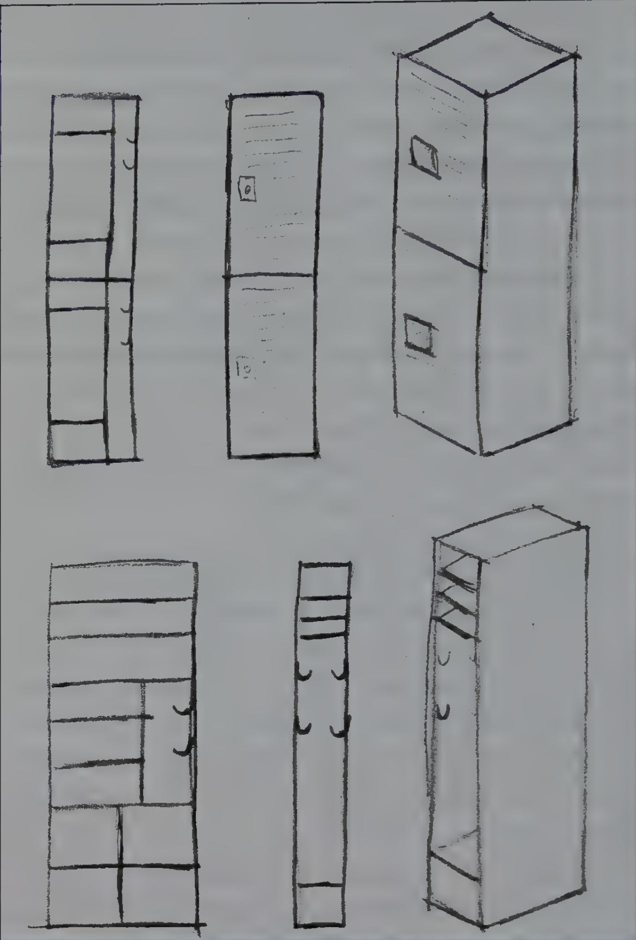

Figure 2-7.

These sketches will be refined further in the solution creation step.

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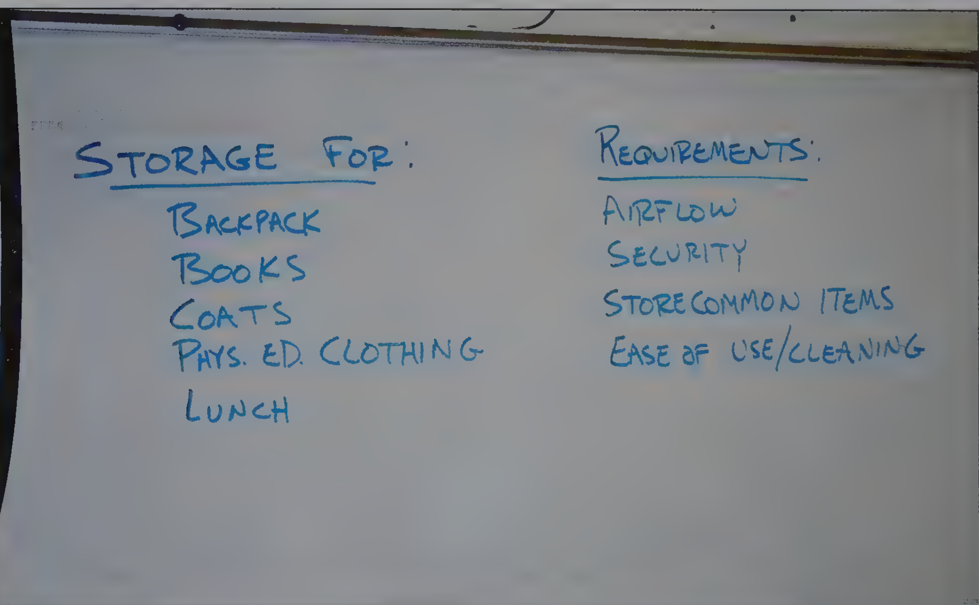
Figure 2-6.

This whiteboard is being used to brainstorm different ideas concerning the need for new lockers.



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Detail drawings are not made at this point. Simple ***sketches*** usually are made to record and communicate ideas so they can be refined further in the solution creation step.

Research is another good way to develop alternate solutions. Engineers do research in libraries, on the Internet, through the United States Patent and Trademark Office, and in other areas. Engineers speak with experts in the field and others with firsthand knowledge of the problem at hand. Engineers often purchase products that are already on the market to see how they work and to see how they can be improved.

Solution Creation

The goal of the solution creation step is to sort through all the ideas from the idea generation stage and decide on the best possible solution. This is the stage where each idea is evaluated and tested to see if any will truly solve the given problem. If more than one solution solves the problem, the best solution must be selected and refined.

There are many ways to begin evaluating proposed solutions from the idea generation step. One way is to throw out all ideas that do not truly solve the problem. Once the list is narrowed down to ideas that could work, the process of finding the best solution can begin. The process of evaluating ideas is called design analysis. Each idea is evaluated based on its cost, size, shape, appearance, performance, difficulty to produce, ergonomics (ease of use), marketability, functionality, safety and liability, ethical considerations, and other criteria specific to the problem.

Each design must be evaluated based on the criteria for the design listed previously. There are many methods and techniques for evaluating ideas against criteria. One way is to rank all criteria in order of its importance. A numeric value is then given to each of the criteria. Each idea can then be given a numeric score based on how well it meets the given criteria. It is imperative that numeric values are scores that are assigned in an objective way so the decision is based on facts rather than simply selecting someone's favorite idea. All other factors being equal, the idea with the highest numeric score is the best solution given the criteria, **Figure 2-8**.

The final step in the solution creation step is to communicate the solution. Rough sketches were made in the ideation step to record ideas. Now it is time to create full-color renderings, detail drawings, and three-dimensional (3-D) models so other people can understand the chosen solution.

Renderings are full-color drawings that show what the object will look like in a given light. See **Figure 2-9**. These can be hand-drawn or computer-generated renderings.

Detail drawings are technical drawings that accurately communicate size and shape. They usually include specific dimensions for others to see.

Three-dimensional (3-D) models can be made by hand out of products like clay, plastic, wood, and foam. They can also be drawn using 3-D ***computer-aided drafting (CAD)*** software. CAD software is often used to create drawings in order to communicate design solutions. Rapid prototyping machines are used to create 3-D models. Equipment using

Design Evaluation

Criteria	Design #1	Design #2	Design #3
Appearance	7	3	6
Cost	2	8	3
Function	6	4	9
Production	5	7	8
Safety	6	5	7
Design Score	26	27	33

Figure 2-8.

Design evaluations are used to rate and select designs.

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Figure 2-9.

Renderings show the designs in a given light.

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computer numerical control (CNC) converts the CAD models into 3-D shapes. Computer-aided manufacturing (CAM) software converts the CAD drawings to machine tool paths. Tool paths are the paths or tracks that the tool follows. Picture an engraving tool cutting your name into a brass plaque for an award you have won. The cutter bit will scratch your name into the brass similar to the way you write your name with a pencil. The letters of your name become the tool path.

Engineers might find during the solution creation stage that none of their ideas actually solve the problem or that none of the ideas are feasible. They may also discover completely new ideas or ways to improve on current ideas. They may find it necessary to move back to the idea generation step. They may even have to redefine the problem or reevaluate the criteria for the solution.

Test/Analysis

Once the best solution has been chosen and communicated, it is time to test and analyze that solution. There are many ways to test solutions. Engineers are responsible for selecting the test(s) that best evaluate their solution against the stated criteria. For example, it is critical to test the aerodynamics of a new wing design in a wind tunnel, but there would be no reason to use a wind tunnel to test a new keyboard design.

Where possible, ***computer simulations*** are used for testing because they take relatively little time and money to set up and run, but much can be learned. Picture a 3-D computer simulation of the operation of a new drive linkage for a mountain bike. Computer simulations show if the parts fit together properly, if there is any interference between moving parts, and the speed at which the bike moves in a given gear when the pedals are moved at a given speed. Tremendous knowledge can be gained without having to invest the time and money to actually build the bike.

Prototypes are also used in testing. ***Prototypes*** are physical models of a final product or some aspect of a product. Prototypes can be made from the material that will be used for the final product or of another material like foam or clay. See **Figure 2-10**.

Figure 2-10.

This prototype can be used to test the new design of the locker.

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Math

Ratios and Scale

Objects are often too large to fit on the available paper, or they are too small to be seen on paper at their normal size. Drawings can be scaled up or down in order to meet the needs of the reader. The concept of scale is something you will need to understand in order to create sketches and drawings of designs. A scale is a means of communicating the size of the design on paper relative to the size of the actual designed object. Scales are communicated in ratios.

Imagine you are designing a new four-wheeler, and you need to communicate your drawing on standard 8 1/2″ × 11″ printer paper. The four-wheeler you have designed measures 50″ tall and 60″ long. You could scale it down by a factor of ten for printing. A scale of ten to one can be shown as the ratio 10:1. This means each inch on the paper is equal to 10″ for the real design.

10:1 = 50:5

10:1 = 60:6

50″ scaled by a factor of ten equals 5″. 60″ scaled by a factor of ten equals 6″. Therefore, your design of the 50″ × 60″ four-wheeler shown at a scale of 10:1 is shown as 5″ × 6″.

For the following problems, use ratios to scale the design up or down to fit on standard 8 1/2″ × 11″ printer paper.

1. A 72″ × 60″ oven.
2. A 1″ × 2″ MP3 player.
3. A 4 ″ × 8″ office phone.
4. A 52″ × 36″ television.
5. A 60″ × 84″ bookshelf.

Prototypes can simply be the outside shape of an object at full scale, scaled down, or scaled up to meet the needs of the test. Picture a full-scale clay model of a new sports car painted to look like the finished product. A model like this can be tested in a wind tunnel for aerodynamics or shown to potential customers to test the market for such a car.

Sometimes full-scale working prototypes are made to test all aspects of a new design. For example, a new office chair can be made as if it came off the production line. The prototype could be given to people in offices, where it would be used in its real environment. The people who use the chair then provide feedback to the engineers about what they liked or disliked about the chair.

CNC lathes, routers, mills, and other equipment are used to cut prototype parts out of solid pieces of materials like wood and metal. Designs are created using CAD software, and the parts are made by the machines. Parts that might have taken hours or days to make using conventional means can now be made in a matter of minutes.

Rapid prototyping is increasingly popular because it is a fast and affordable way to move from design to prototype. Rapid prototyping machines build solid models by laying down many thin layers of material until the entire shape has been created, **Figure 2-11**.

During the testing and analysis step, it could be discovered that the solution does not work or it is not the best possible solution. It could be too costly to produce, it may not be strong enough to perform the desired task, or market analysis could show that people are not willing to buy it. Engineers may discover a new idea for a design that is better. They can take this new information back to the appropriate step in the design process and work back through it until they have the best possible design solution.

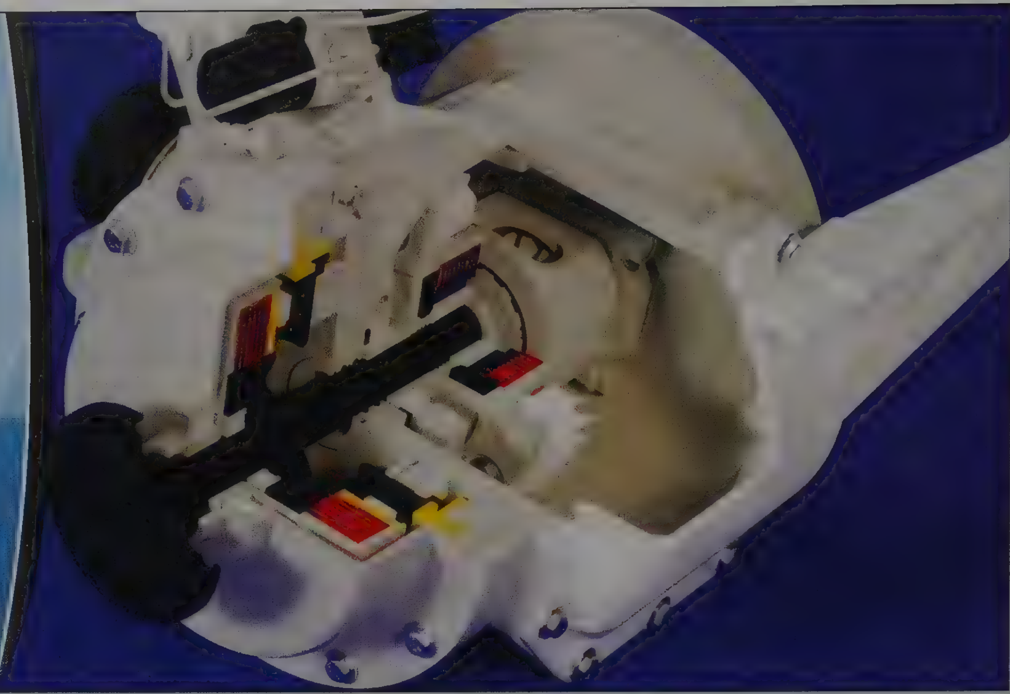

Figure 2-11. Rapid prototyping machines build models layer by layer until the desired shape has been created.

Stratasys, Inc.

Final Solution or Output

Once a design passes the testing/analysis step, it is ready to be manufactured or built. The next job for the engineer is to accurately and completely describe the design solution to the people who will make it. Engineers put together a set of documents that includes drawings and specifications for the part(s) to be made.

In order to communicate a design idea, drawings must be created. There are many different kinds of drawings. Each type of drawing is used to serve a specific purpose.

Design solutions are communicated using mechanical drawings. ***Mechanical drawings*** are highly accurate technical drawings meant to communicate the size and shape of objects in great detail. These drawings can be created using a conventional drawing board and manual tools, but are most often created using CAD software on a computer. Pictorial and orthographic drawings are typically used to communicate the shapes.

Pictorial drawings show a single view of an object, but show it in a way that makes it look 3-D as your eye would see it. See **Figure 2-12**. Pictorial drawings are easy for the viewer to see and understand. They are often used to show people what

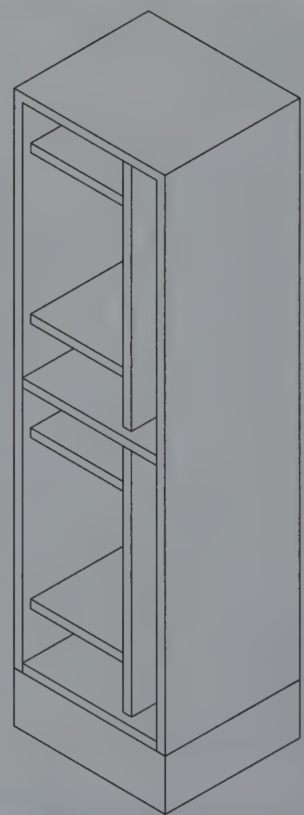

Figure 2-12.

This pictorial drawing shows a single view of the locker design.

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the overall shape will look like. Because they are drawn to look 3-D, the angles within the drawing are distorted and are not completely accurate.

Orthographic drawings, also known as ***multiview drawings***, are the true shape, and show what a part will look like from a given direction. Refer to **Figure 2-13**. They are called *multiview* because it is usually necessary to include more than one view of an object to completely communicate the shape and size. Orthographic drawings are usually dimensioned, meaning that there are notes on the drawing to communicate size,

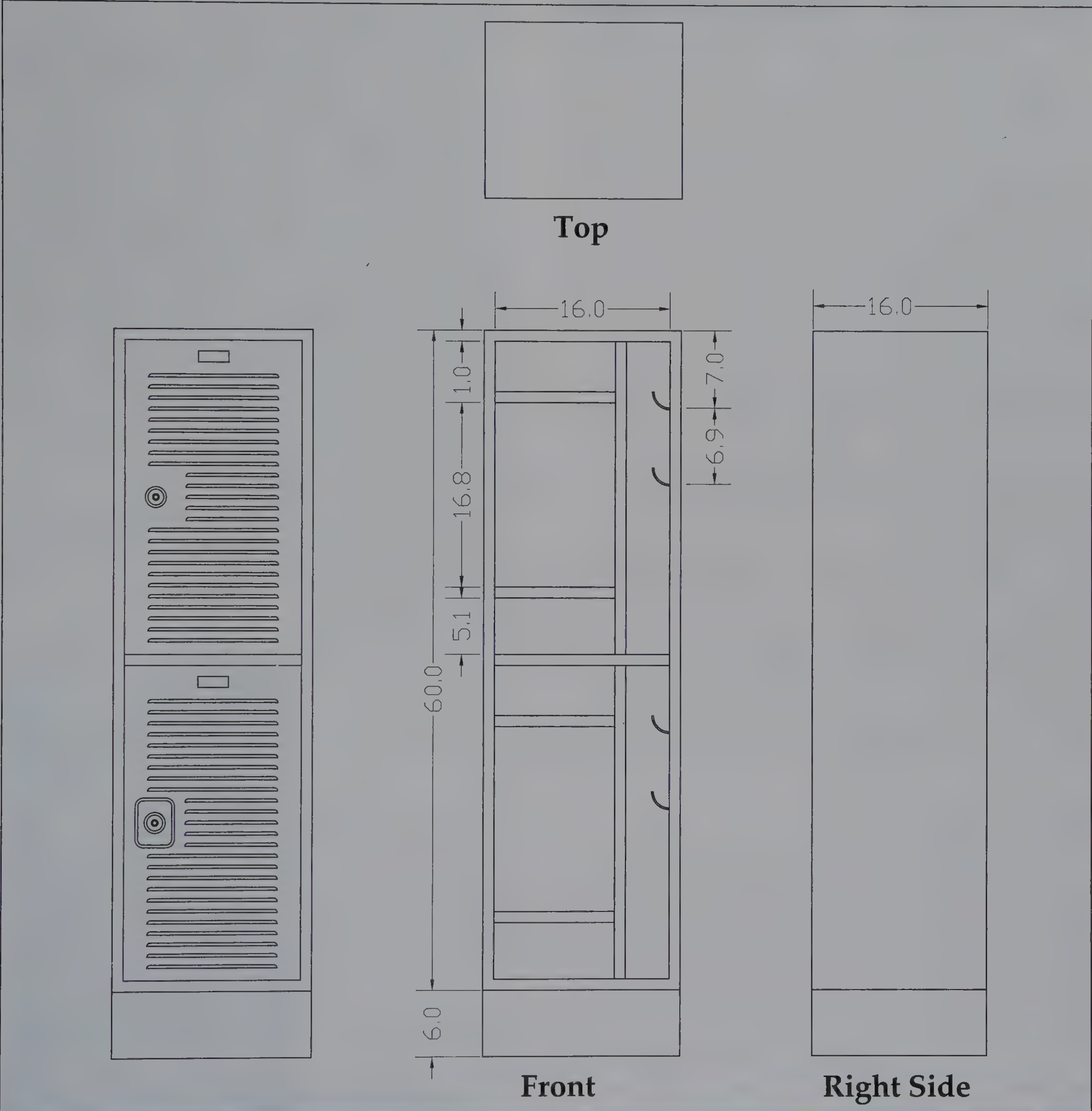

Figure 2-13.

This example of an orthographic drawing shows several views of the locker design.

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History

Engineering Design in History

Thomas Edison is often credited with inventing the incandescent lightbulb. He did not actually invent the lightbulb, but rather improved the lightbulb that had been invented long before.

Modern incandescent bulbs use a tungsten filament surrounded by an inert gas inside a globe. Electrical current flows through the filament, heating it and causing it to glow and create light. The gas is used to replace the oxygen in the air because the filament would burn up if oxygen was present.

Problem Definition

There were two types of lights at the time. The electric arc lamp created light using an electric arc, but they were far too bright for most indoor applications. The incandescent light of the day had too low a resistance and therefore used too much electricity.

Idea Generation

Edison determined that he needed to design a filament that would glow when current was passed through it but had a high resistance so it would use less electricity than the bulbs that were currently available. It also had to last for an acceptable period of time. Edison developed literally thousands of ideas.

Solution Creation

Edison sorted through his ideas and picked the most promising one before moving on to the testing step. He had little idea if an idea would meet his needs until he tested it.

Testing/Analysis

Edison tried the thousands of filaments and evaluated their performance. This process went on for years until he found a material that made sufficient light, had a high resistance, and lasted for an acceptable period of time. He had materials shipped to him from all over the world so he could experiment with them as filaments. Each time an idea failed, he had to return to the idea generation step and start over. His persistence and patience led to his success.

Final Solution or Output

When an idea passed the testing step, it became a final solution. Edison's lightbulbs were later sold as electric lighting caught on.

Design Improvement

Each time he had a successful test, he started over trying to find a filament that was even better. He continued to improve on his own success.

angles, hole specifications, threads, finish, and all other pertinent information.

Specification sheets provide the necessary technical information to the builder or manufacturer of the product. The specification sheets include the exact material to be used, how it is to be made, specific parts to be included, tolerances (acceptable variation from limitations), and more. The specification sheets ensure the product will be made to the exact requirements of the engineer.

When the drawings and specifications sheets are complete, they are sent to management or clients for final approval.

Design Improvement

No design is perfect, and all designs can be improved in some way. Although a product has been identified as the best possible solution to a problem, is past the testing stage, and has gone into production, there is still room for improvement. From the time a product is made, people will redesign it to be cheaper, safer, more effective, or to meet some other need.

Products must be constantly improved to keep up with advances in technology and the demands of the marketplace. Companies are in direct competition to increase their share of the market. They are

constantly redesigning products in an effort to gain an edge and increase profits.

Once a product hits the market, companies can benefit from a wealth of feedback regarding their product. This information can be used to strengthen the design.

Engineers can take a design back to any of the steps in the design process, make changes, and work back through the process, **Figure 2-14**. This is how many products keep getting cheaper, safer, smaller, and more effective.

Engineering Notebooks

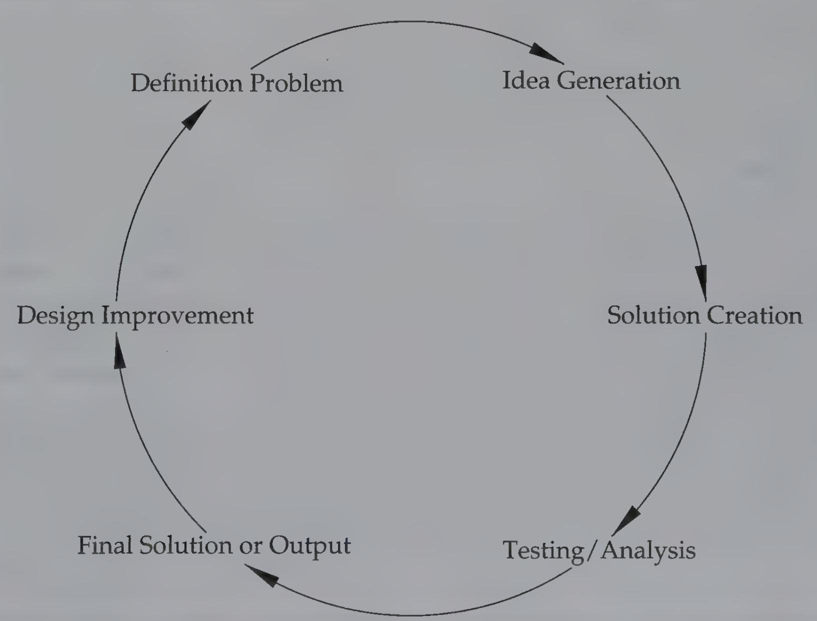
Engineers typically record all their thoughts, ideas, sketches, calculations, designs, and more in engineering notebooks. An engineering notebook is an effective way to record all the information from every step of the design process in one place in case you need to access it in the future. If they are kept properly, engineering notebooks can be legal documents if there are ever disputes over intellectual property. Intellectual property refers to the legal rights to the creations of the mind. Engineers, artists, inventors, designers, and others have specific rights to their original work and ideas. Artistic and literary works are protected under copyright laws. Industrial property, such as inventions and designs, are protected under patent law. If an engineer comes up with a new idea or invention that could be worth a lot of money, he or she has sole rights to that idea as long as the proper steps are taken. It is very important for engineers to keep engineering notebooks in a legal way that will protect their ideas in the future.

For legal purposes, it is important to use a notebook with a fixed binding so that no pages can be added or removed. Books are available with lined paper, blank paper, or graph paper. Graph paper might be the most useful so sketches can be made easily. See **Figure 2-15**.

The notebook should serve as a written record of everything that happened with regard to a given project. It should include every idea, sketch, thought, group activity, observation, success, and failure. These records can be of great help throughout a project and even long after the project is over. Information gained solving one problem could help to solve other problems in the future.

It is important to think of the engineering notebook as a legal document. No pages should ever be added or removed. Most engineers date their books each day so they have an exact record of when everything happened. There should be

Figure 2-14.
Designs can be improved even after a product is created.



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Going Green

Renewable Resources

We use wood and wood products every day. Wood is used in most houses in the United States for framing, exterior wall sheathing, roof sheathing, flooring, trim, and cabinets, **Figure A**. Think about the amount of paper consumed in your school in a year, or even in a day. Wood and wood products are a valuable part of our daily lives.

Wood is a renewable resource. Renewable resources are resources that can be replenished in a reasonable amount of time. If our forests are managed properly, our forests will never be depleted. Wise and sustainable forest management programs provide for the harvest of this valuable resource while using replanting techniques that ensure the forest will be there for future generations.

One of the biggest problems with logging, or cutting trees for timber, is the impact of the massive harvesting equipment on the forest floor. Skidders, haulers, and other equipment can tear up the forest floor, causing increased erosion. The heavy weight of the equipment can compact the soil and damage or even kill trees. Until now, most harvesting has been done with machines using large tires with heavy tread or tracks. A harvester is a machine where the operator sits in a cab and can use the machine to cut down, delimb, and cut trees to desired length for pickup by another machine. See **Figure B**.

Engineers are now designing harvesters that walk through the woods softly on legs and create almost no impact. There are no tires or tracks to damage the forest floor. A well-protected driver sits in a climate-controlled cab and operates the machine with a joystick. It can move forward, backward, side to side, diagonally, and rotate in a circle. It can even vary the distance between the cab and the ground. Typical equipment requires clearing and leveling paths for travel while the harvester can step over obstacles in its path. Sensors on its feet tell it what the forest floor looks like so it can adjust accordingly. It can do all this while minimizing the negative impacts on the rest of the forest and the trees that are not being cut down so they can remain healthy.

People often think of technological advancements as having a negative effect on the environment. Our society needs wood and wood products to maintain our way of life. Trees are one of our greatest renewable resources. Selective cutting can actually improve the overall health of our forests. The walking harvester is an advancement in design and engineering that allows us to harvest this valuable renewable resource while minimizing the negative impacts on the overall health of the forest. It is important to remember that engineering designers are often on the forefront when it comes to renewable resources and environmental management.


Figure A.
David Lee/Shutterstock.com


Figure B.
Dmitry Naumov/Shutterstock.com

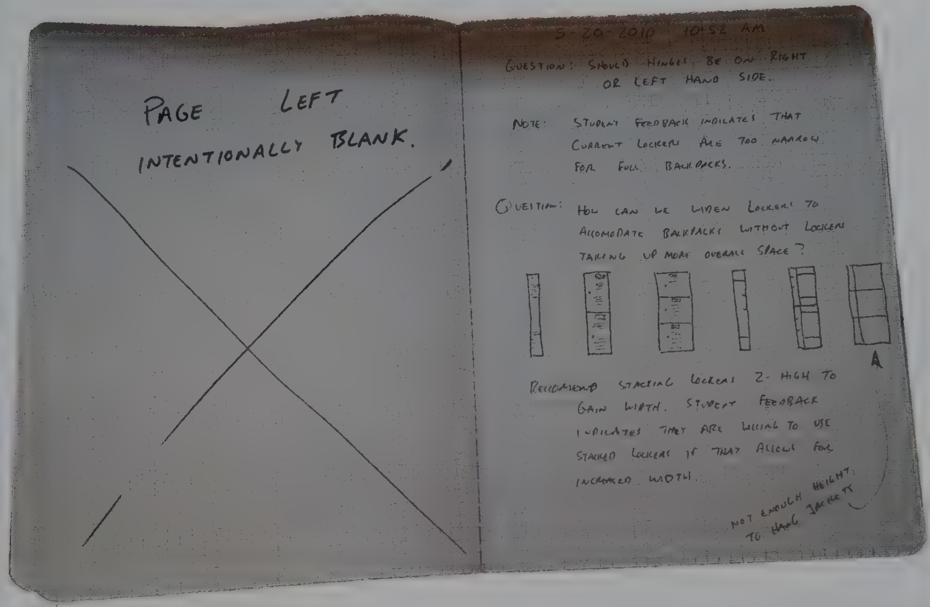

Figure 2-15.
Sketches can be made easily on graph paper in an engineering notebook.

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no blank pages. If there is a blank section, a large *X* should be drawn over it. No work should be covered up with correction fluid or scratched out so much that it is not longer legible. If something must be crossed out, it should be done with a single line so it can still be read. All writing should be neat enough for others to read so they can verify the work. Enough detail must be given so that others can understand the concepts.

As long as it is maintained properly, your notebook can help prove the exact moment you discovered that your idea would solve the problem, the exact moment you verified that your solution would work through testing, how to build and use your solution, and your due diligence in working to solve the problem.

Summary

- All human-made things around us have been designed to meet some need or want.
- Engineering design is the creative application of technology to design systems, products, and processes to solve problems.
- Engineers create solutions to problems using the engineering design process.
- Engineers must use all steps of the design process, but can also go back to any step and start over if the need arises.
- Defining the problem is the first step in the engineering design process. Resources can be wasted when the problem is not properly identified.
- Constraints must be defined after the problem has been identified.
- Ideation techniques include brainstorming and researching.
- Evaluating designs is the first step in creating solutions.
- In the solution creation step, solutions are communicated through renderings, detail drawings, and 3-D models.
- Solutions can be tested using computer simulations and prototypes.
- Final design ideas are communicated using mechanical drawings, pictorial drawings, orthographic drawings, and specifications.
- All designs can be improved in some way. Products are constantly being redesigned to be cheaper, safer, more effective, or to meet some other need.
- Keeping an engineering notebook is an effective way to record all the information from the design process in one place in case you need to access it in the future.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. Who creates design problems?
2. _____ involves finding not just a solution, but the best possible solution given a specific problem and criteria.
3. What are the six steps of the engineering design process?
4. _____ is arguably the most important step in the design process. Large amounts of time and money are wasted if mistakes are made at this step.
   A. Solution creation
   B. Idea generation
   C. Final solution
   D. Problem definition
5. The _____ outlines the problem in clear terms.
6. What information is included in a design brief?
7. Brainstorming is most effective when done _____.
8. In the _____ step, all ideas are evaluated and the best one is chosen to move forward.
   A. solution creation
   B. idea generation
   C. final solution
   D. testing/analysis

9. _____ drawings are created in the solution creation step.
   A. Mechanical
   B. Pictorial
   C. Orthographic
   D. Detail
10. Which is of the following is *not* used in the testing/analysis step?
   A. Engineering notebooks.
   B. Multiview drawings.
   C. 3-D modeling software.
   D. CNC machines.
11. A(n) _____ drawing shows what a part will look like from a given direction.
12. _____ are used in the final solution or output stage to communicate necessary technical information to the builder or manufacturer of a product.
13. *True or False?* The engineering design process is complete when a final product is made.
14. When do design engineers start on the design improvement step?
15. Describe how engineering notebooks are used.

Reinforce *learning*

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

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Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 3

Defining Problems and Brainstorming

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Key Terms

brainstorming web
common constraints
criteria
free association
freewriting
future process
problem
specific constraints

Practice *vocabulary*

Objectives

After studying this chapter, you should be able to:

- Identify steps used to define problems.
- Describe how constraints and criteria are involved in the engineering design process.
- Explain the goals of brainstorming.
- Identify different brainstorming techniques.
- Explain the importance of problem definition and idea generation to the engineering design process.

The engineering design process is used to develop solutions to everyday problems. For example, engineers have developed many different methods over time to move people and cargo from different locations in the world. From the early days of horses and buggies to our modern methods of using automobiles, trains, and airplanes, these solutions have been developed to solve one basic problem—the need to move people or cargo quickly and safely from one location to another.

The problem in the example above was defined before solutions could be developed. Clearly defining the design problem is a critical stage in the design process. This stage includes identifying the problem, writing the problem statement, and generating the criteria and constraints. After the design problem is defined, you can begin to generate ideas to develop design solutions. See **Figure 3-1**.

Throughout the design process, engineers work in teams. Design teams are developed to identify and solve engineering-related problems. The teams include engineers, engineering technicians, and tradespeople. The design team is created around a specific problem, and the team includes specialists related to the specific topic. If a team is assembled to design a new electrical system for a school building, the team may include electrical engineers, structural engineers, as well as engineering technicians and tradespeople who will create and install the solution. One member of the team will be selected as a project manager. The project manager is usually the member of the team with the most experience, as well as an ability to organize and manage engineering projects.

Defining the Problem

Defining the problem is the first step in solving a problem. A ***problem*** is a question, something that is needed for a design, or something that needs to be changed in a design. Engineers are often faced with solving important problems. For example, imagine your town has had a large snowstorm, and people cannot drive on the roads or walk on the sidewalks because of the heavy amount of snow. The inability to navigate around the town is a problem. It is important the problem is solved so students can get to school, employees can get to work, and emergency personnel can travel the city to assist others. To solve this problem, engineers have developed snow removal equipment, such as plows and shovels, to help us move large amounts of snow quickly and efficiently.

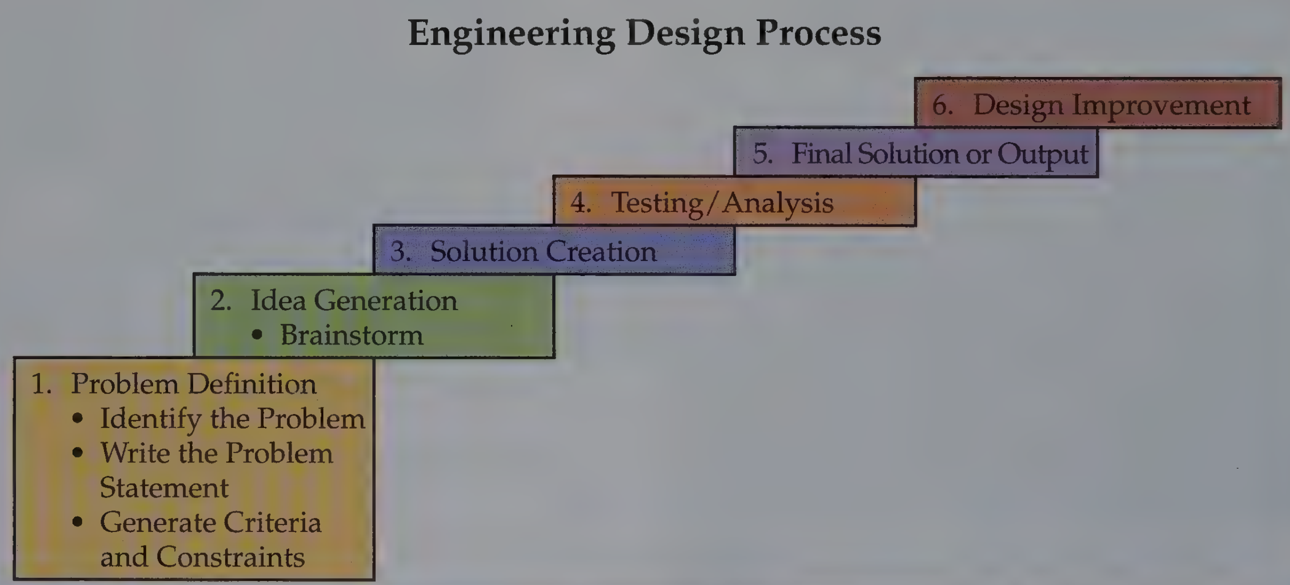

Figure 3-1.

There are three steps contained within the problem definition step: identify the problem, write the problem statement, and generate criteria and constraints. Brainstorming is the first part of the idea generation step.

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There are many factors to consider when defining a problem. First, there are different types of problems. Some are clear, while other problems are unclear and missing specific details. Engineers regularly address clear challenges. For example, a mechanical engineer may be presented with a problem of increasing a gearing ratio in a mechanical device. The engineer is given the exact ratio size and must design the pieces. While this challenge still requires very strong technical knowledge, it is a very straightforward challenge because the engineer is given all the necessary information and requirements.

However, engineers often encounter challenging problems that are unclear and difficult to identify. For example, a manufacturing engineer may be challenged with increasing the efficiency of an assembly line system. See **Figure 3-2**. Given very little specific information and considering the system uses many different electric motors, as well as pneumatic and hydraulic power, there could be many different solutions.

Engineers must make sure they clearly identify the actual problem as part of the engineering design process. Mistakes in identifying the problem can cause wasted time and resources toward solving the wrong problem. By clearly identifying the problem, engineers also ensure all members of the design team are working on the same problem. Engineers are often asked to solve problems given to them by other members of their company or directly from customers. Therefore, they must make sure they identify the actual problem to be solved and have clear communication with coworkers and customers.

Steps to Identifying Problems

Engineers define problems by going through different steps. Some complex problems require engineers to spend more time going through each step. Four steps that help engineers identify the problem are explained below. It is important that all four of these steps be considered when identifying the problem:

1. Determine the problem's origin.
2. Define what is and what is not the problem.
3. Identify the present state and desired state of each component in the problem.
4. State the problem in your own words.

Engineers use an engineering notebook to record their thoughts and discussions about the problem. They record responses to the previous four steps in their notebooks. The notebook is used throughout the design process as a way to document a solution and to be able to redesign or revisit ideas.

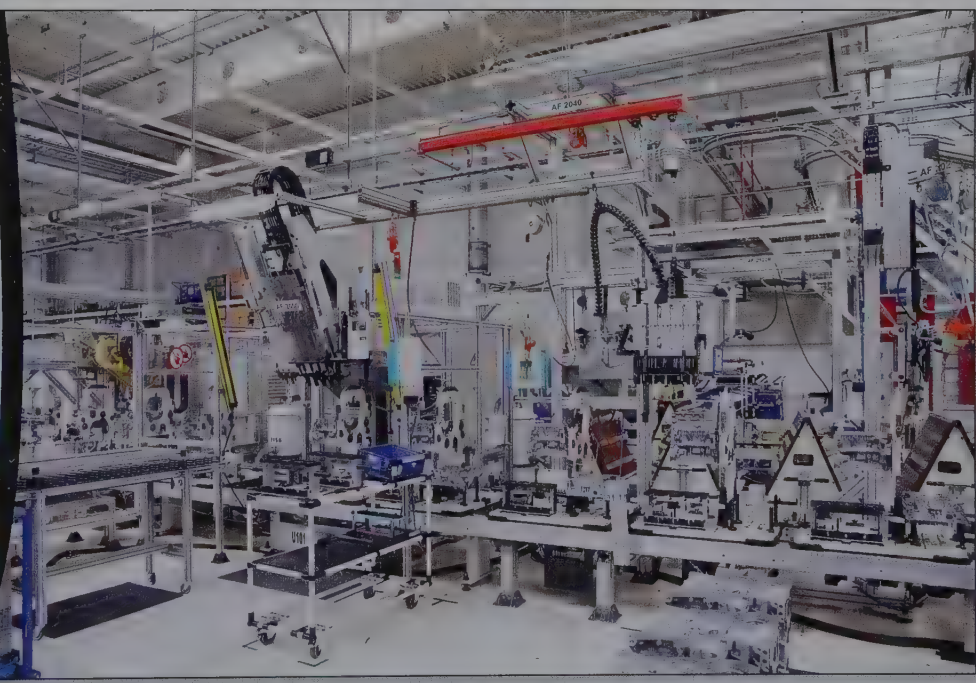

Figure 3-2.
Increasing the efficiency of an assembly line is an unclear problem.

Nataliya Hora/Shutterstock.com

First, engineers ask where the problem came from. By asking this question, engineers can look at the problem from the very beginning. Understanding the problem's origin helps clarify what needs to be solved. One common problem for families, businesses, and other organizations is the amount of energy used in their structures. The electricity used to power buildings can be expensive and uses valuable resources to create. To define the problem of too much energy use in your school building, engineers might ask:

- How much energy is being used in the school?
- Could the problem be with the furnace, lighting, or insulation?
- How much energy would we like the school to use?

The next step to identify the problem is to determine what the problem *is* and what the problem *is not*. This step is extremely helpful in solving different types of engineering problems, such as automotive, electronic, and mechanical challenges. Engineers use this process by making a list. The list has two columns, which are labeled *Is the Problem* and *Is Not the Problem*. See the example shown in **Figure 3-3**.

Looking at the problem of improving energy efficiency in the school, engineering design teams will investigate the current school systems. This is done to determine the efficiency of the current systems and identify if each is or is not the problem.

Is the Problem	Is Not the Problem
Electrical system	Insulation system
Fixtures	School structure
Delivery system	

Figure 3-3.

This chart helps engineers determine what is and what is not the problem.

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Design teams might first look at the electrical system for lighting. If the system uses outdated fixtures and electrical delivery systems, teams will add these to the *Is the Problem* list. Teams will also look at the insulation system in the school. This will help them determine if the structure of the school and insulation systems are sufficient. These will be put on the *Is Not the Problem* list. See **Figure 3-4**.

The next step in defining a problem involves looking toward the desired solution. Identifying the present state and the desired state helps engineers clarify the problem to ensure they meet the proper goal for the problem's solution. To use this step, set up a chart like the one in **Figure 3-5**. This chart has two columns, one labeled *Present State*, the other labeled *Desired State*. Begin by listing the present state of the problem and for each item you list, write a response in the *Desired State* column.

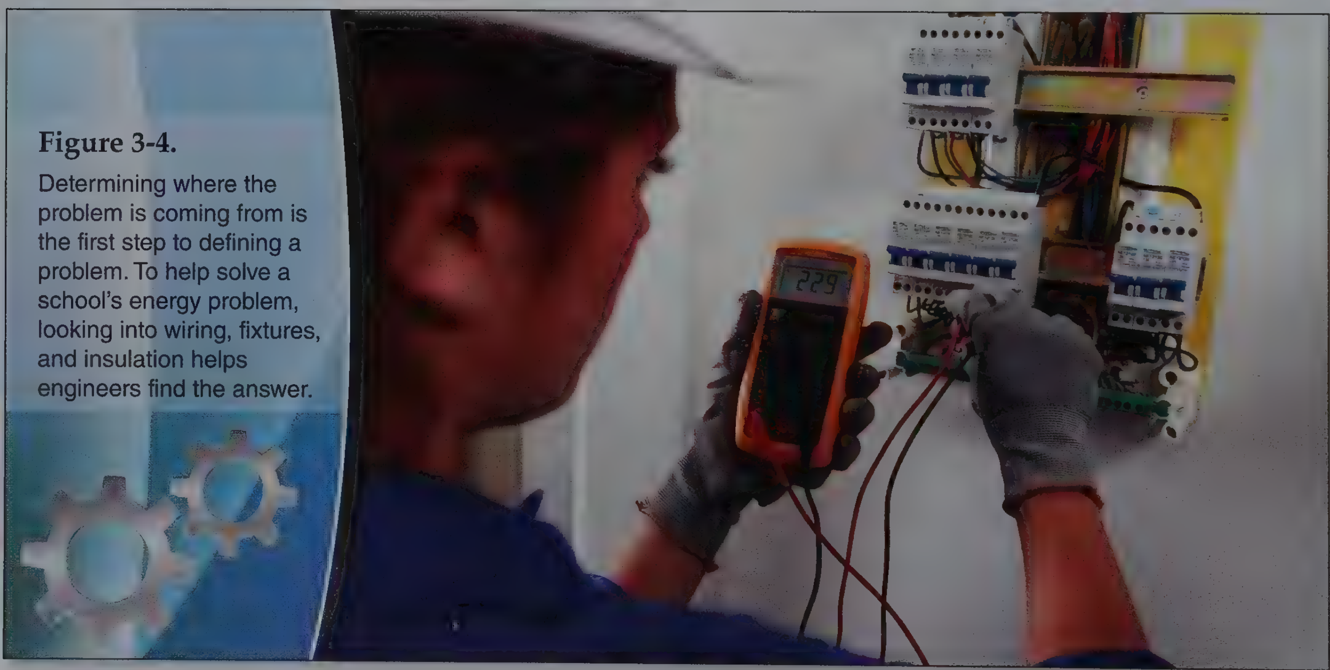

Figure 3-4.

Determining where the problem is coming from is the first step to defining a problem. To help solve a school's energy problem, looking into wiring, fixtures, and insulation helps engineers find the answer.

auremar/Shutterstock.com

Present State	Desired State
Low efficiency for lighting system	Use 65% less energy for lighting system
Low efficiency for heating and cooling system	Update to high-efficiency heating and cooling system

Figure 3-5.

A chart showing the present states of various components of the problem helps engineers determine their goals for the desired states of those components.

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For example, revisit the school's energy efficiency problem. The engineering design teams have investigated the different systems in the school and have found the efficiency of the different systems. These systems include electrical, lighting, insulation, structure, and heating and cooling systems. Through discussions with tradespeople, engineering technicians, structural engineers, electrical engineers, and energy professionals, they have determined the different levels of efficiency needed for each system. Engineers have determined the present state of the lighting systems and heating and cooling systems is not desirable. The engineers determine their desired state is to use 65% less energy out of the lighting system than the current incandescent fixtures and bulbs in the classrooms. Also, the engineering team determines they should adjust the heating and cooling system to improve the system to a desired high-efficiency method.

The final step in identifying the problem is to state the problem in your own terms. As previously mentioned, engineers are often given problems by other members of their design team or customers. Engineers need to be able to state the problem in their own terms to ensure they understand the problem.

Writing the Problem Statement

Once engineers write the problem in their own words, they share the problem with their customers and other team members so everyone understands the problem to be solved. Engineers write the problem statement into their engineering notebooks for documentation and for making further adjustments as needed. As discussed in Chapter 2, a problem statement outlines the problem in clear terms without limiting creativity in design. When you write a problem statement, be sure to address the following aspects:

- **Who is the problem for?** A problem must have value for it to be worth solving. It will be valuable to someone, such as a person or company. The statement should address who will be using/impacted by the solution.
- **What is the functionality of the problem?** The problem statement should describe the function of the problem that needs to be solved. Examples of functions include whether the design should move an object, repair a system, or fix a leak.
- **Where is the problem located?** You have already learned that the origin of the problem is important in order to identify the problem. The location of the problem may also be critical to the solution.
- **How much?** Is cost of money, materials, or time involved? Some problems may include these factors as part of the defined problem. These constraints will be addressed prior to brainstorming.
- **Is the problem measurable?** The problem statement should have a measurable component so you know if you have solved the problem. For example, you may need to create a crane that will lift a certain amount of weight. The desired weight should be written into the problem statement.

The problem statement should be clear and should not restrict the design. Therefore, the following aspects should also be taken into account when you prepare a problem statement:

- **Problem statement should not be a question.** Make your statement clear and direct by using language that encourages you to accomplish the task. For example, *we will* solve the problem.

- **Problem statement should not give a potential solution in the question.** Do not limit yourself by constraining your problem too much. Do not put potential solutions in the problem because it may limit your creativity. Define the problem, but allow your brainstorming session to find potential solutions.
- **Problem statement should not state why or how.** The problem statement should not be a lengthy explanation of the history of the problem, just a clear statement about what needs to be solved.

Problem statements can be effectively shared in one or two sentences. For example, listed below are sample problem statements:

- We will develop a vehicle that will carry one person 100 miles on a single gallon of fuel in less than 2 hours.
- We will create a method of moving 300 lb. of cargo 27′ every minute during a two-hour time frame.
- We will develop a vehicle that will move five pennies a total distance of 20′ using a mousetrap as a power source.
- We will create a device to protect the structural integrity of an egg throughout a 10′ drop.
- We will develop energy systems to improve the long-term cost and efficiency of our school building by at least 40%.

Forming Hypotheses

Instead of generating ideas after defining a problem, the second step of the scientific method involves forming a hypothesis. A hypothesis is a prediction. It can also be seen as a guess. Not all predictions and guesses, however, are hypotheses. A scientific hypothesis must meet certain criteria in order to work within the scientific method.

One criteria of a hypothesis is that it must be able to be tested. The test(s) must be able to be duplicated as well. An example of a guess that can be tested is, "This ball will bounce if I drop it." This would be considered a hypothesis. A guess that could not be tested is, "Ghosts are real." There is no way of testing whether this could be true, so it is not a hypothesis.

Another criteria for a hypothesis is that it must be able to be disproven. A guess is not a hypothesis if there is no way to prove that it is false. A guess that says, "If there is life on other planets, then it is silicon-based life" cannot be proven false. Therefore, this prediction is not a hypothesis. Even if it can be tested and silicon-based life is found on another planet, this does not mean that all beings on other planets are silicon based. Every planet and any life on those planets would have to be found and tested.

There are two common types of hypotheses. Both types help determine cause and effect. One type of hypothesis is the "if, then" type of hypothesis. The other is the null hypothesis.

An everyday example of the "if, then" type of hypothesis is, "If I water the plants every day, then they will grow." This type of hypothesis helps you know how to test it. In this example, water your plants and see if they grow.

A null hypothesis helps to disprove ideas. An example of a null hypothesis would be, "The stability of my computer is unaffected by a gaming software program." If your computer stops responding continually, you may try to determine which program is causing the issue. When all other variables, or in this case other programs, are removed, it is easier to decide the gaming program is causing your computer to stop responding. The hypothesis, therefore, is disproved.

A hypothesis is not proven to be true. It can always be disproven in some way. Once a hypothesis has been tested repeatedly to find the same results, it becomes accepted as a scientific theory.

Generating Criteria and Constraints

As you define the problem and write the problem statement, you explore the problem's criteria and constraints. ***Criteria*** are guidelines to follow in order to successfully solve the problem. As discussed in previous chapters, a constraint is a limitation of the design solution, such as size or cost. In this section, we will look at the different types of criteria and constraints encountered by engineers on a regular basis and see how engineers incorporate these criteria and constraints into their designs.

Criteria

In engineering design, criteria help guide engineers in order to successfully solve the problem. Criteria are often confused with constraints, which are limits to the design. Criteria take constraints into consideration and are seen as an outline for the design of a potential solution. For example, design criteria for improving the efficiency of the school's energy may be that it must improve efficiency by 40%, it must be able to use renewable resources when possible, and it must allow each classroom to use similar lighting fixtures to improve adaptability.

Criteria are critical in the development of an engineering design solution. Engineers list the criteria in their engineering notebooks to make sure they are following the proper guidelines. Without the criteria guidelines, engineers can lose focus on their designs and not solve the correct problems. Engineers also use a list of constraints to help keep the limitations in mind as they are developing the solution.

Constraints

Constraints are limits on the design and can be challenges to overcome. Constraints provide a guide for solution creation by keeping a design within limits. Clarifying the constraints early in the design process is critical to ensure designs will be able to solve the problem in an appropriate way. The two types of constraints are common constraints and specific constraints.

Common constraints are conditions that are in all engineering design problems. For example, all design solutions must be legal and safe for people to use. Also, a common constraint may be that the design is ethically appropriate for users and the environment. These types of constraints are in every design and are the foundation of an engineer's approach to designing safe and appropriate products.

Specific constraints are conditions that are directly related to the engineering design problem at hand. Specific constraints move beyond the large-scale common constraints and help determine how engineers will design their solutions. Specific constraints are unique to each design, but some common examples are size, cost, marketability, and look and transportability of the product.

To explore the constraints in an engineering design problem, it is important to create a list of all of the common and specific constraints for the problem. Engineers list the constraints into the two categories, as shown in **Figure 3-6**. The list of constraints is shared with other team members and customers.

Common Constraints	Specific Constraints
Use safe materials and products	New systems must fit into the current building structure
Use materials and supplies that are available locally	Solution must use a specific power source
	New mechanical systems must be located in a specific area of the school
	Project cannot exceed a certain amount of money for total construction

Figure 3-6.

Engineers use a list of common and specific constraints to help guide their designs.

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History

Brainstorming in History

Engineers often design solutions that may not be best for the current problem but that may solve another problem. Throughout history, different solutions that did not solve the intended problem were found to solve other problems. These accidental solutions make up many products we use today. Some ideas may not solve your current problem, but they may be helpful to others in the future.

Post-It Notes

Spencer Silver was trying to design a strong adhesive for the company 3M™. Silver developed a weak adhesive that could easily be lifted off any object to which it was attached. A colleague of Silver named Arthur Fry was using pieces of paper for place markers in a book. The pieces of paper kept falling out of his book, and he remembered the weak adhesive developed by Silver. Fry tried some of the adhesive on his pieces of paper and it worked. The company created Post-It® Notes from this accidental solution.

Microwave

During World War II, engineers designed a tool called the magnetron, which was used by the British to spot enemy war planes. Percy LeBaron Spencer worked with some of the magnetron radar technology, which emits microwave radiation. One day, Spencer accidentally melted a candy bar that was in his pocket. He realized that using the microwaves from the radar cooked food. Raytheon began researching and testing the microwaves, and the company produced their first microwave oven in 1954.

Teflon

The technology used to make pans with a slippery, nonstick surface is Teflon™. Dr. Roy Plunkett was working with refrigerant when he and his design team created polytetrafluoroethylene, also known as Teflon. By compressing tetrafluoroethylene, they accidentally created the waxy solid that would coat products for many years to come. The first Dupont Teflon™ product was introduced in 1945.

Pacemaker

Pacemakers are devices implanted into patients' chests to help keep their hearts beating at a constant pace. Wilson Greatbatch was working on a device that recorded irregular heartbeats. While creating his device, Greatbatch grabbed the wrong type of resistor from a box. Greatbatch noticed the device would pulse at regular intervals. This solution became the pacemaker in 1960.

When we look at the problem of improving the energy efficiency of the school, engineers need to consider different constraints. First, engineers list the common constraints to improve energy efficiency in any building. Examples of common constraints are that the solution must use safe materials and products, and it must use materials and supplies that are available locally.

To determine more specific constraints for this project, the engineers meet with school district personnel. The specific constraints may be that the new systems must fit into the current building structure, the solution must use a specific power source, and any new mechanical systems must be located in a specific area of the school. See **Figure 3-7**. A specific cost constraint may be that the project cannot exceed a certain amount of money for total construction.

Researching Criteria and Constraints

Once the criteria and constraints are developed, engineers research to investigate projects that have addressed similar problems. Engineers look to verify that their criteria and constraints are appropriate for the problem through analysis of similar situations. They ask themselves several questions. What do others see as constraints? Are these constraints under our control? What external constraints must we consider? Is this criteria appropriate for this design?

Figure 3-7.

The constraints for providing more energy efficiency to the school may include limited amounts of space. Installing solar panels on the roof is a potential solution that meets these constraints.

Mik Lav/Shutterstock.com

Brainstorming

The next step of the engineering design process is idea generation, in which engineers generate potential solutions to solve the problem. Idea generation consists of brainstorming and researching. Brainstorming is an important way to generate ideas. The primary goal of a brainstorming session is to generate as many ideas for solutions as possible and allow for team members' creativity to work without fear of ideas being dismissed. See **Figure 3-8**. There are different approaches to brainstorming, but almost all of the brainstorming models incorporate the following four principles:

- Develop a large quantity of ideas.
- Do not criticize suggestions.
- Use your imagination.
- Combine and modify ideas.

The goal of brainstorming sessions is to create a long list of possible ideas. Therefore, brainstorming sessions should encourage as many ideas as possible. The leader of a brainstorming session sets a goal for the number of ideas created in the session. This goal should be difficult to reach without exhausting all of the possible ideas. While only one idea will eventually be selected to solve the problem, it often takes discussion about hundreds of different ideas to come to a solution that may work. It is critical to have a team member record all of the ideas to revisit as the engineering design process develops. Sketches are also needed to explain complex designs. It is good to have a large area, such as a whiteboard, available to list and draw potential solutions.

Figure 3-8.

The goal of brainstorming sessions is to generate ideas. Engineers often generate many imaginative solutions to their design problems before developing a final solution.

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Math

Converting Fractions to Decimal Numbers

When creating solutions to problems, engineers rely on measurements and dimensions to determine the overall size of their design. They also use measurements and dimensions in their criteria and constraints. Engineers often write their measurements in the form of fractions, but they often need to convert the number to a decimal number for use in computer software or to communicate with other engineers and manufacturers.

To convert numbers from fractions to decimal numbers, divide the numerator (top number in the fraction) by the denominator (bottom number in the fraction). For example:

$\frac{1}{2} = 1 \div 2 = 0.5$ $\frac{3}{8} = 3 \div 8 = 0.375$

Convert each of the following fractions into decimal numbers.

1. $\frac{3}{4}$
2. $\frac{1}{8}$
3. $\frac{5}{16}$
4. $\frac{7}{8}$
5. $\frac{1}{4}$
6. $\frac{5}{8}$
7. $\frac{27}{32}$
8. $\frac{7}{16}$

Brainstorming sessions are a time for a free flow of ideas from team members, not a time for critiquing other members' ideas. It is critical members of the design team are willing to listen to others and allow ideas to emerge. Judging ideas will inhibit people from sharing their thoughts about potential solutions. It is important the leader of the brainstorming session helps create an atmosphere that welcomes everyone's ideas through respectful and encouraging language. Brainstorming sessions are not designed to affirm or deny any ideas. They are simply meant to create a list of as many ideas as possible.

Engineers use the brainstorming process to discuss any ideas that may have potential to solve the problem. Engineers rely on their experience and training to come up with imaginative ideas. Sometimes imaginative ideas seem silly or too complex, but all ideas are valued at this stage. In fact, some of the world's greatest inventions began as silly ideas during brainstorming sessions.

When engineers brainstorm, they realize all of their ideas may not solve the problem, but they also understand they may be able to combine ideas to create an effective solution. The process of combining and modifying ideas is one of the reasons all ideas are encouraged in the brainstorming process. An ideas that may seem impossible to create on its own may have small parts that can be used in the solution. Small parts from multiple solutions are often combined to create one solid solution.

Brainstorming Techniques

Brainstorming can take many different shapes and formats, but the basis of it begins with someone, or more commonly a group of people, attempting to develop a solution to a problem. Finding the proper approach to brainstorming helps engineers create their solutions. Different techniques can be used for brainstorming, but they all follow the four criteria previously mentioned. Different techniques that may be used to brainstorm are described below.

Free Association

Free association is the act of describing as many ideas as possible without any concern about their ability to be accomplished. This is the

most common form of brainstorming. Free association relies heavily on the ability to brainstorm without being critical of ideas. It also depends on producing a large quantity of ideas. The goal is to use free association to trigger ideas, even if they may be only a small part of the solution, that engineers can then use to solve the problem. The team leader will often give the group a time limit to come up with as many ideas as possible while listing each potential solution on a whiteboard for everyone to see.

Example:

Problem statement:

A manufacturing firm wants to develop a way to move 4′ long 2×4s of lumber from the first floor of their manufacturing facility to the second floor. They need to be able to have a constant flow of materials by moving one 2×4 every minute.

Free association brainstorming session:

To solve this problem using a free association method, the engineering team leader gathers all the members of the team into a room and use a whiteboard to list ideas. The team leader gives everyone 20 minutes to list as many potential solutions as possible. See **Figure 3-9**.

Freewriting

Freewriting is an individual brainstorming technique in which an engineer generates possible ideas by writing them down. This process is usually a timed approach and forces engineers to describe their thoughts in writing, which can help them clarify ideas. Much like free association, all ideas are welcome, but this approach is completed individually and then reported back to the team, unlike the free association, which is normally used as a group brainstorming technique.

Example:

Problem statement:

A computer and office supply company wants to produce a new type of printer ink that will not dry up when in open contact with air for three weeks, but the ink must instantly dry when in contact with paper.

Freewriting brainstorming session:

To solve this problem using a freewriting method, the engineering team leader gives all members of the team a specific amount of time to write and sketch their potential ideas. The leader then gathers all the members of the team into a room and uses a whiteboard to list ideas. See **Figure 3-10**.

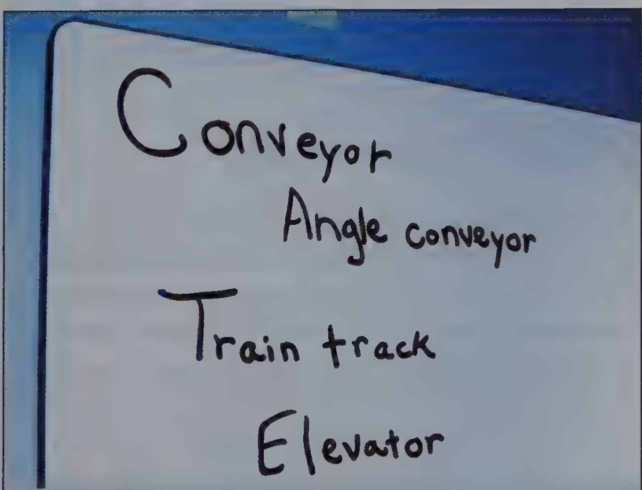

Figure 3-9.

When using the free association method of brainstorming, every idea for a potential solution is listed.

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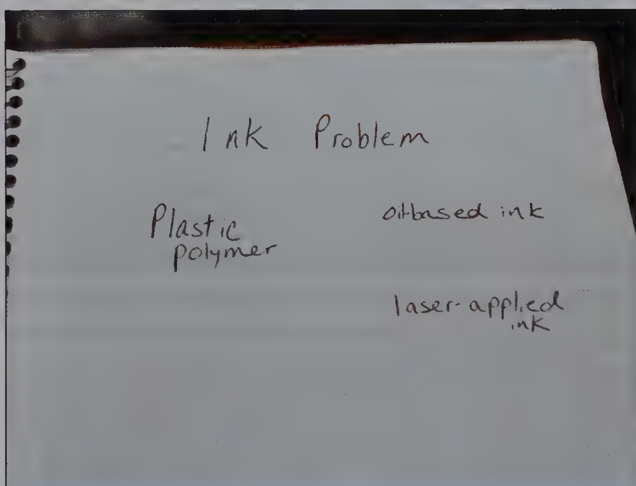

Figure 3-10.

Freewriting can be done by individuals and then shared with a group.

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The Future Process

When using the ***future process***, engineers intentionally focus on solutions that are not possible yet because of technological or scientific limitations. The purpose for this process is for engineers to find the ideal list of solutions without limiting themselves to current ways to produce or manufacture the solution. This type of process helps them identify a solution and work backward to find a way to solve the problem. This type of process can be challenging because engineers are trained to find ways to solve problems as simply as possible. However, at times, it helps for design teams to look at the impossible to come up with ideas that are possible.

Example:

Problem statement:

An automotive company wants to develop a personal vehicle that can safely move individuals very quickly without a major threat for an accidental wreck.

Future process brainstorming session:

The engineering team leader lists potential ideas on a whiteboard in the front of the room. The team leader tells the engineers to focus on technologies that may be available in the future, but are not available now, hoping to inspire some potential solutions. See **Figure 3-11**.

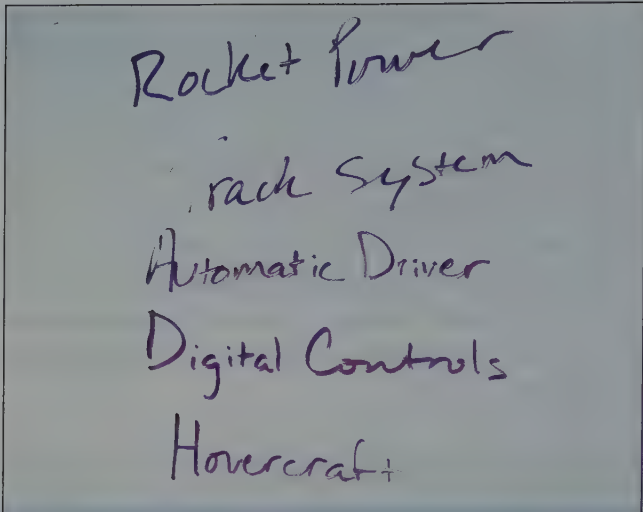

Figure 3-11.

The future process of brainstorming allows engineers to list potential solutions based on technology and procedures they think will eventually be available.

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Brainstorming Web

A ***brainstorming web*** is a method of linking different ideas together by finding commonalities between them. To use this method, the design team lists ideas in a way similar to the free association approach, by writing any ideas that come to mind in a space all members of the design team can see. When using the web approach, however, the ideas are written in random locations on the whiteboard instead of in an organized list. Once engineers have completed listing ideas, the team begins to find links between the ideas. The team leader draws lines between ideas that have a connection, and a "web" of ideas is developed through their commonalities. This approach is used to create an avenue to combine and modify ideas. The web method is especially helpful when the solution has multiple components.

Example:

Problem statement:

Improve energy efficiency in household refrigerators, allow food to stay as cold as possible, while keeping it a standard size and operating on 110 V.

Web brainstorming session:

The engineering team leader explains to the group to list as many potential ideas as possible on the whiteboard and then link them together using a web. See **Figure 3-12**.

Initial Outcomes

As illustrated in this chapter, the first steps in the engineering design process are critical in the development of solutions to our everyday problems. The key to these steps is to generate a clear description of the problem and as many potential solutions as possible. Once engineers have completed the brainstorming process, they have a list of ideas that may need to be modified, integrated together, or revisited to come up with a workable solution. In the next chapter, we will look at how engineers select the best solution from a brainstorm list and research potential designs.

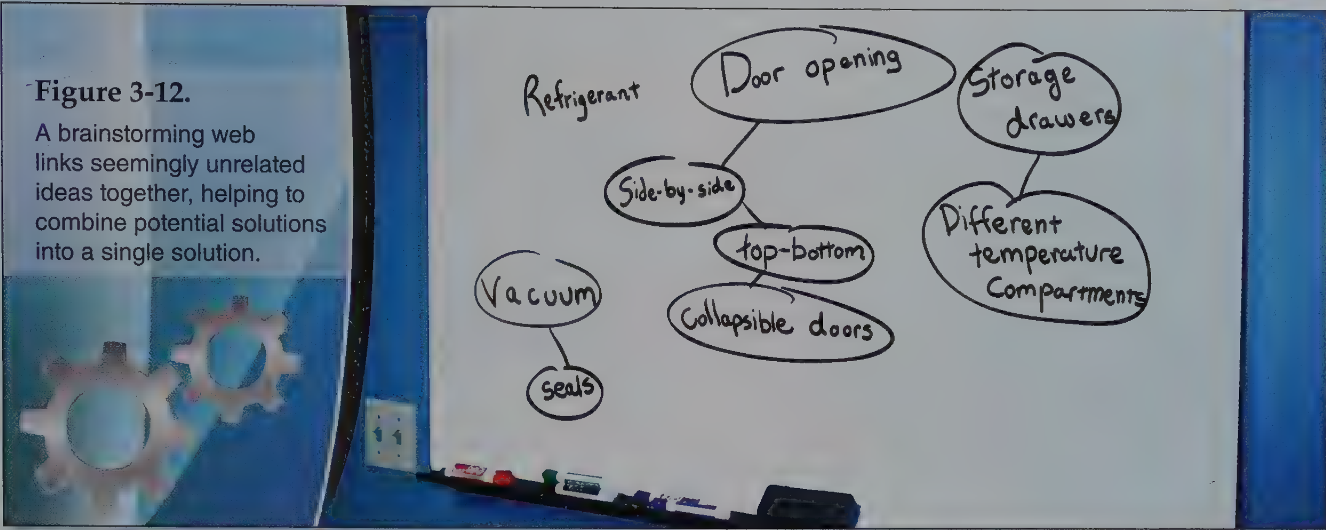

Figure 3-12.
A brainstorming web links seemingly unrelated ideas together, helping to combine potential solutions into a single solution.

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Going Green

Floating Cities

The identification of needs, development of appropriate criteria, working within certain constraints, and brainstorming solutions is critical to designing appropriate green technological solutions. Engineers are currently developing more advanced green solutions to problems they cannot build. They believe the technology will be available in the future to manufacture and produce these solutions.

Many examples of engineers developing futuristic green solutions exist, but floating cities may be as cutting edge as any design with a chance to be produced in the future. The use of floating cities is a solution to the potential of rising water levels. Scientists believe the ocean levels are rising and this may change the way we may live in the distant future. To address this potential concern, engineers and designers have begun to design floating cities. See **Figure A**.

Figure A.

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Many different ideas for floating cities exist, including the *Lilypad Project* and the *Freedom Ship*. Some engineers believe these floating cities will create a biologically sound community on top of the ocean that can adjust to rising and sinking water levels. These communities may be able to house up to 50,000 residents. These floating cities could be used in emergency situations for housing of natural disaster victims, and the communities could move to other locations due to their mobility.

These man-made islands could not be efficiently produced right now, but it may be possible hundreds of years from now. In this case, engineers have looked to the future and defined a potential problem, assessed the needs of future generations, and brainstormed a possible solution. Floating cities are an example of engineers performing green brainstorming, anticipating a future need.

Summary

- Clearly defining the design problem is critical. This stage of the design process includes identifying the problem, writing the problem statement, and generating the criteria and constraints.
- Some problems are clear, while other problems are missing specific details.
- The problems engineers are faced with often require the use of mathematical, scientific, and technical knowledge, as well as background knowledge.
- In order to identify problems, engineers must determine the problem's origin, define what is and what is not the problem, identify the present state and desired state of each component in the problem, and state the problem in their own words.
- Several aspects must be addressed when writing a problem statement, including who benefits from solving the problem and the functionality and location of the problem.
- As you define the problem and write the problem statement, you explore the problem's criteria and constraints.
- The two types of constraints are common constraints and specific constraints.
- The primary goal of a brainstorming session is to generate as many ideas for solutions as possible and allow for team members' creativity to work without fear of ideas being dismissed.
- Four techniques used in brainstorming are free association, freewriting, the future process, and a brainstorming web.
- Once engineers have completed the brainstorming process, they have a list of ideas that may need to be modified, integrated together, or revisited to come up with a workable solution.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is a *problem*?
2. _____ knowledge allows you to easily identify some problems because of your previous experiences.
3. What is the first step to consider when identifying problems?
4. Which step in identifying problems helps engineers better define the goals for a problem's solution?
   A. Define what is and what is not the problem.
   B. Identify the present state and desired state of each component in the problem.
   C. State the problem in your own words.
   D. Write the problem statement.
5. Guidelines that need to be followed in order to successfully solve the problem are included in the _____.
   A. problem statement
   B. criteria
   C. constraints
   D. solution
6. _____ can be challenges to overcome and keep a design within limits.
   A. Problems
   B. Criteria
   C. Constraints
   D. Specifications

7. Safety in design is a(n) _____ constraint.
8. Cost is an example of a(n) _____ constraint.
9. List the four requirements for an effective brainstorming session.
10. What is freewriting?
11. Describe the future process of brainstorming.
12. Describe the brainstorming web process.

Matching: Decide whether each aspect of the problem should be included in the problem statement or not.

13. The functionality of the problem.
14. A potential solution for the problem.
15. The cost of money, materials, or time involved.
16. Who the problem is for.
17. The history of the problem.
18. The location of the problem.
19. Measurability of the problem.
20. State why or how.

A. Include in the problem statement
B. Do not include in the problem statement

Reinforce *learning*

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

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Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 4

Researching Designs

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Key Terms

- cost feasibility
- discussion forum
- experimental research
- library research
- refined sketch
- research
- rough sketch
- thumbnail sketch
- trade-off

Practice vocabulary

Objectives

After studying this chapter, you should be able to:

- Explain how to communicate potential solution ideas using sketches.
- Describe different types of library research.
- Identify properties found through experimental research.
- Analyze trade-offs in engineering design.
- Explain how to select the optimal solution.

Once engineers have brainstormed potential ideas, they begin the process of sketching and researching the potential design solutions. Once the initial brainstorming is complete, design teams narrow the potential list of ideas to a manageable list to research. Narrowing the list of ideas allows the engineers to look at realistic ideas that may solve the problem. Engineers typically begin to look at how practical the potential solutions are to design and manufacture in order to remove ideas that are not possible to create. ***Research*** is a scientific way to discover facts about a certain topic or situation. Most professionals use research techniques to help them solve problems. Lawyers research court cases to advise their clients, police officers research a crime scene to find information, and teachers research topics so they have accurate information to share with their students. Engineers use research to develop the best solution to solve a problem.

After the brainstorming stage of the idea generation step of the engineering design process, engineers sketch and research different potential solutions. Design teams may have engineers focus on a variety of designs to determine the most effective solution. The parts of the idea generation step, including sketches and research, may be completed on many different designs to select the best approach. See **Figure 4-1**.

Sketches

Engineers must have an idea they can communicate to begin researching the potential solutions. Engineers can share their ideas of what the design may look like and explain the functionality of the solution by putting their ideas on paper. See **Figure 4-2**. To communicate these ideas, engineers first develop sketches. Sketches are any drawings that can communicate the engineer's idea to others. There are several types of sketches.

Rough sketches are the first drawings completed by engineers. Rough sketches are normally developed during or immediately following the brainstorming session. Rough sketches are drawings of solutions that are in the early stages of development. "Rough" does not mean they are bad or inaccurate drawings. Rough sketches just need further development through research and analysis. Engineers are not concerned with the quality of the sketch; they just want to make sure they have a record of their ideas in their engineering notebook.

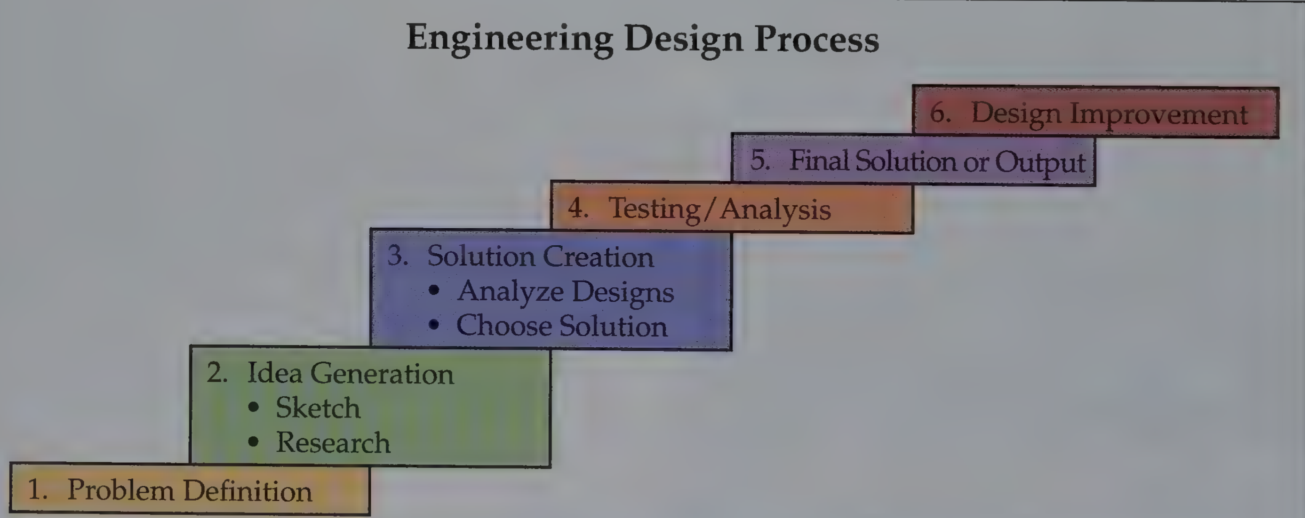

Figure 4-1.

After brainstorming, the idea generation step includes sketching and researching.

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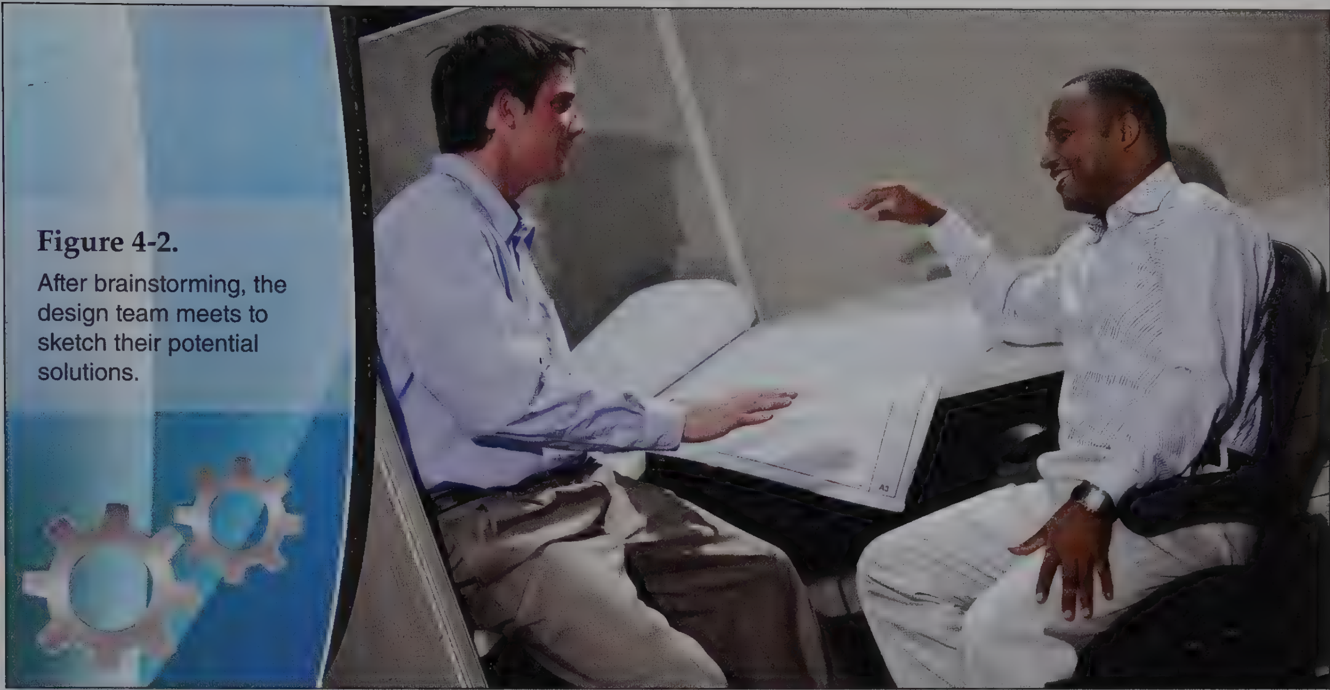

Figure 4-2.
After brainstorming, the design team meets to sketch their potential solutions.

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See **Figure 4-3**. Engineers also want to make sure they have the overall shape and size of the product, realizing that it may change drastically as they research and further develop the design. Rough sketches can be drawn to large or small scale. Another term used for rough sketches is ***thumbnail sketches*** because of their small size.

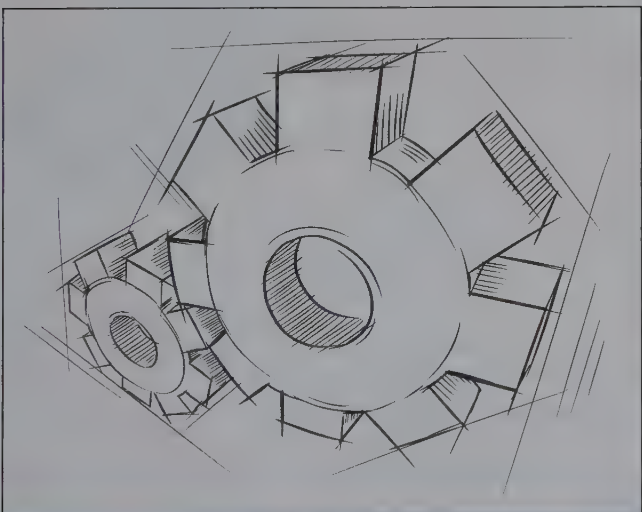

Figure 4-3.
Rough sketches, or thumbnail sketches, are drawn by hand in engineering notebooks so engineers have a record of all their ideas.

aggressor/Shutterstock.com

An aerospace engineer may have an idea for the shape of a new fuselage for an airplane. The company will develop rough sketches of the overall look of the fuselage without actual dimensions and missing some of the overall components of the design, but it will be enough to communicate the design with members of the engineering design team. A rough sketch may be of a small component of a much larger device. For example, a mechanical engineer may draw a rough sketch of a gearing system for transferring power from one component to another in a wind turbine.

Rough sketches are important because they provide a way for the engineer to communicate their ideas. It is important for the engineer to be able to move design concepts from ideas to a potential design solution to a problem. Sketches also allow others to see the ideas and offer suggestions to improve the design. Finally, rough sketches provide a concrete object to begin thoroughly researching the potential effectiveness of the design.

Sketching Process

Sketches are critical to begin formulating ideas for a design solution. Now with advanced computer modeling (described in Chapter 6),

sketches are often the only noncomputerized method of planning a design. Ideas are often taken from the initial sketches, researched, and then manipulated using computer software.

The sketching process follows four basic steps:

1. Visualize the solution.
2. Block out the solution.
3. Outline the solution
4. Detail the solution.

Visualize the Solution

First, the engineer visualizes the appearance and the functionality of the object. The functionality, or the way the object works, is typically of the most concern to an engineer. The engineer begins by visualizing the operation of the object. Usually, engineers see the object in three dimensions, but they might also view the object from the six different sides of the object. See **Figure 4-4**.

Block Out the Solution

Once the visualization of the object is developed, the engineer begins to block out rough shapes. Sketching solutions usually requires a combination of boxes, cylinders, cones, and pyramids. With knowledge of blocking out these shapes, engineers are able to create most sketches. The engineer uses light lines to represent the rough size and shape of the object. These fine lines are used as guidelines to create more detailed views of the object.

Isometric drawing methods make an object appear three dimensional on a two-dimensional object, such as paper or a computer screen. Isometric drawings are used to give a real-world appearance of an object by showing the front, top, and side views, just as the eyes see the object.

Boxes are used to block out many shapes. To create a box to draw a feature, the engineer first draws a vertical line as the front corner. Then the engineer draws one line on each side of the front corner. Then the engineer connects the lines at the top and bottom using roughly a 30° angle. The box is then completed by drawing two lines parallel with the lines going to the front corner to create the top of the box. See **Figure 4-5**.

Cylinders are often used to create a rough block for an object. See **Figure 4-6** to draw a cylinder. Drawn an isometric square containing an ellipse, or an isometric circle. Draw a duplicate square above the first square by drawing vertical lines of equal lengths from each corner of the original square and by connecting the points. An ellipse is drawn inside the new square.

Cones and pyramids are drawn using a box. An *X* is drawn on the top of the box to determine the center. The center point of the *X* will be the top point of the cylinder or cone. Lines are drawn from the top center point to each bottom corner of the box to create a pyramid.

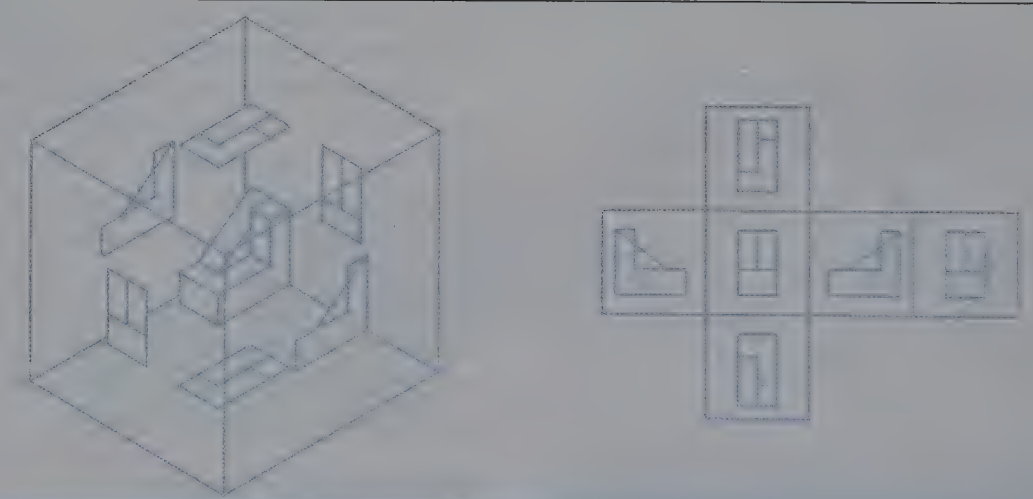

Figure 4-4.

Engineers view objects in three dimensions, but they may also look at each of the six sides of an object individually.

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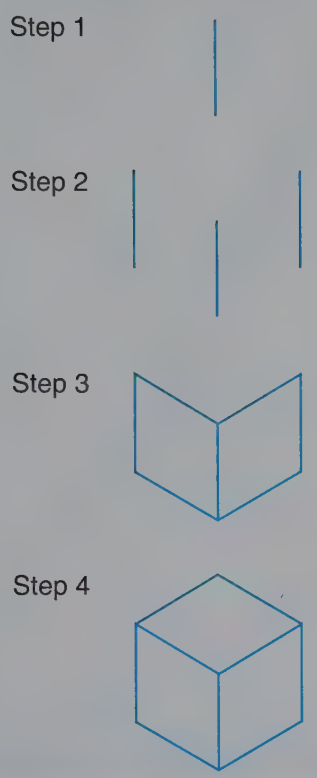

Figure 4-5.

Boxes are sketched using these steps.

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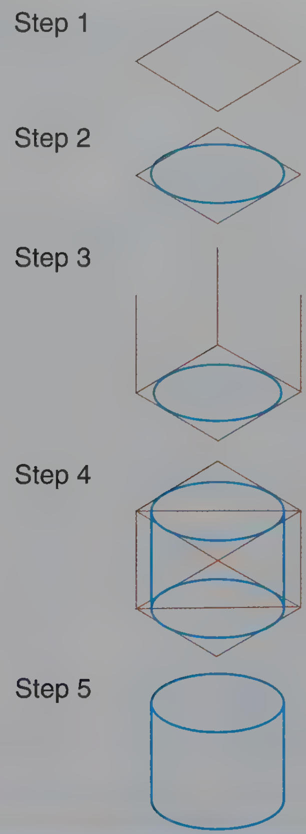

Figure 4-6.

Cylinders are sketched using these steps.

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Math

Calculations with Circles

Circles cannot be measured in the same way straight lines are measured. The three key values when measuring circles are radius, diameter, and circumference.

The radius of a circle is half the width of the circle from its center. The radius is represented in equations by r. The diameter of a circle is the full width across the center of the circle. In equations, diameter is represented by d. To find the diameter of a circle, multiply the radius by 2.

$$d = 2 \times r$$

Circumference is a measure of the perimeter of the circle. Circumference is represented as C in equations. Another value used in measuring circles is pi, represented as π. Pi is a fixed number equal to about 3.14.

To find the circumference of a circle, multiply the diameter of the circle by pi. If you do not know the diameter, multiply the radius by two, then multiply the product by pi.

$$C = d \times \pi$$
$$C = 2 \times r \times \pi$$

Find the circumference of the following circles using the information given.

1. $r = 2.5$
2. $d = 45$
3. $d = 350$
4. $r = 0.5$
5. $d = 1.5$
6. $d = 83$
7. $r = 0.03$
8. $r = 6.2$

To create a cone, an ellipse is drawn in the bottom of the box and lines are drawn from the top center point to each end of the ellipse. See **Figure 4-7**.

Outline the Solution

Creating a detailed outline is the next step of completing a sketch. Engineers use many different lines when creating sketches, including outline lines. An outline is the basic shape of the object. Outline lines are removed from the sketch, leaving object lines to appear on the final drawing. Outlines are drawn very lightly because all the lines will not be included in the final sketch. Engineers know they will add and remove many lines before the drawing is complete. See **Figure 4-8**.

Detail the Solution

Details are the final component added to a sketch. The details include all the components of a design that are not a part of the main shape that was blocked using boxes, cylinders, and other shapes. See **Figure 4-9**. Details may include curved shapes of a car, the strings on a guitar, or the company name on a television.

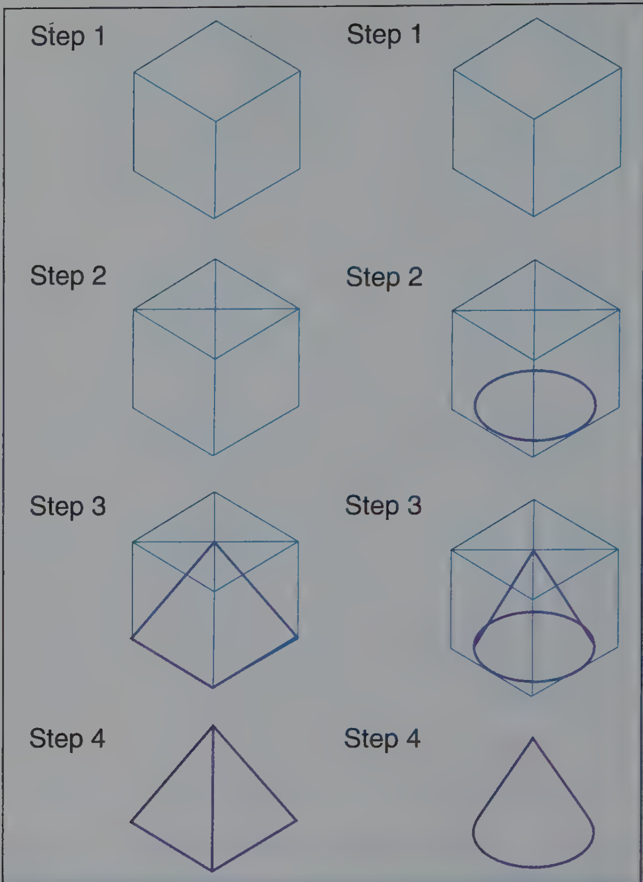

Figure 4-7.

Pyramids and cones are sketched using the steps shown.

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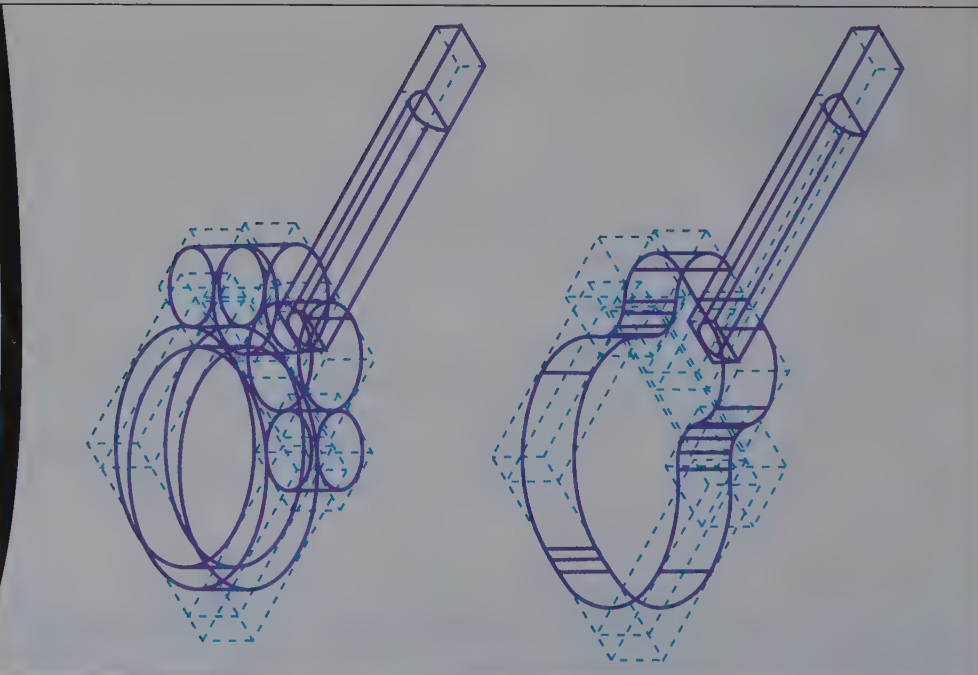

Figure 4-8.

A sketch of a guitar is first blocked out using boxes and cylinders. Then, an outline of the guitar is created, showing the external shape.

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Figure 4-9.

This sketch of a guitar includes the details of the external features.

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Researching Ideas

Engineers use different types of research to develop an understanding of the problem and the potential solutions. Engineers look at how solutions have been solved in the past, review the mathematical and scientific principles used in a potential design, and survey potential users of the design. To gain an understanding of each of these areas, the engineer performs historical research and experimental research. This research will be conducted for many potential research solutions.

Historical Research

The first place engineers look to gain information is solutions that have solved similar problems. Engineers often develop innovative designs, but they do not invent new technologies. They first look at how they can adapt current technologies and tools to solve the problem. This type of research is conducted using different methods, including library research, field visits, and discussions with other engineers and professionals using the technology.

Tools

Drawing Compass

Engineers use many different tools to create drawings. While computers are often used for completed designs, engineers still use manual drawing tools for sketches of potential solutions.

One example of a manual drawing tool is a drawing compass. A drawing compass is used to create circles of a certain diameter. See **Figure A**. If you need to draw a circle and a compass is not available, you can use a piece of string, thumbtack, and pencil to create your own compass. Attach the thumbtack on one end of the string and attach the pencil at the desired distance (radius) from the thumbtack.

To use the compass, place the pointed end of the compass (or the thumbtack) where you would like the center of the circle. Move the pencil end of the compass half the width of the circle you desire (radius) away from the center, and rotate the compass around the center point.

Figure A.

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Library Research

The first step in researching potential solutions is to gain insight through printed and digital materials. ***Library research*** is a type of research that uses different forms of printed and digital materials as a source of information. These materials provide images and descriptions that help engineers develop workable solutions to problems. Library research includes using books, magazines, and the Internet to find information.

The first type of library research is the use of books. Books can provide many engineering ideas. Books can show historical use of different technologies and engineering principles. See **Figure 4-10**. This historical information provides the engineer with a thorough background of the history of designs and how their solutions may be developed using historical technologies as a model. Engineers take notes and photocopies of useful material from books and place them in their engineering notebook for future reference in the development of their solution.

Books currently come in many different formats. Engineers now have greater and quicker access to more information through the use of eBooks as well as the use of traditional, printed books. Some materials are only available in print, but eBooks are growing in popularity.

Engineers may also look in catalogs and magazines for potential solutions. Magazines and catalogs are printed materials that are often more up-to-date than books. Catalogs and magazines usually have images of new technologies and ideas in all areas of engineering. By using these types of materials, engineers look at recent trends in design, manufacturing, and other areas of engineering focus.

Digital media has become increasingly important in engineering design. Digital media is a combination of many different tools engineers use including digital images, the Internet, and electronic databases. Engineers use the Internet as a tool to research current designs and for quick access to images and information. The Internet can be used to quickly search magazines, catalogs, and books for relevant information. See **Figure 4-11**.

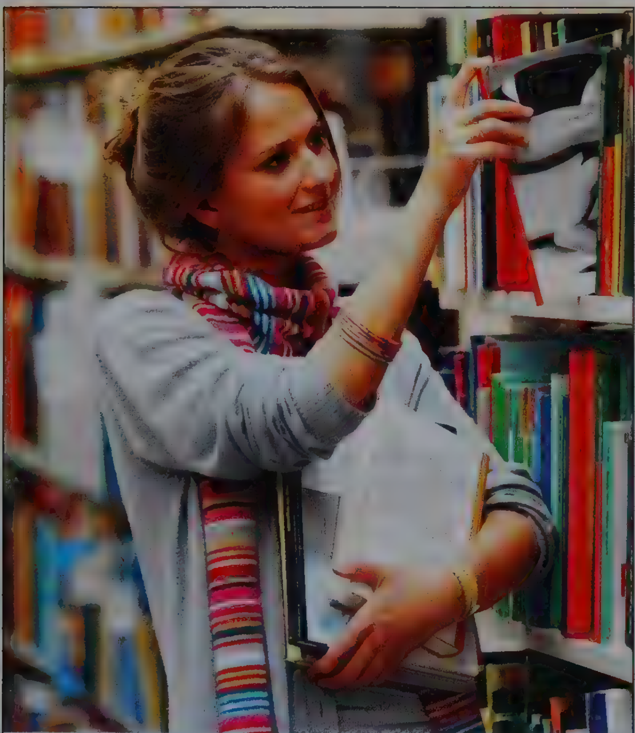

Figure 4-10.

Using books to find information is one type of library research.

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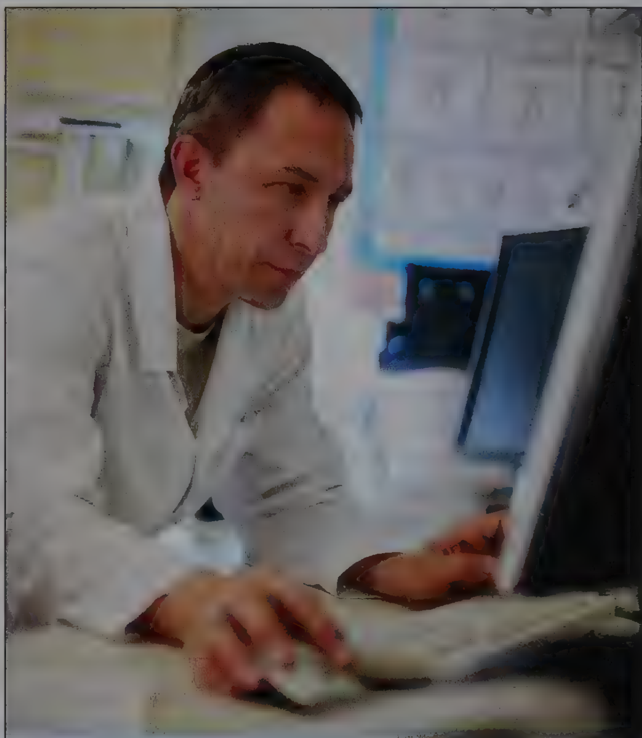

Figure 4-11.

This biological engineer can research solutions on his computer using the Internet.

Konstantin Sutyagin/Shutterstock.com

Engineers must use all of the tools available to them to create the most effective design. The use of electronic media has become imperative in the development of solutions. Engineers use electronic databases as a resource for many things, such as determining the strength of specific materials or checking the amount of support needed to hold a structure. Electronic databases may be websites with archived information, or they can be software programs. Most engineering design software programs contain information on material properties. The time engineers spend looking up information in trade journals or resource books can be made more efficient by using a simple search in a database system to find the needed information. The Internet and databases are also a great tool for engineers to share their findings with other engineers and to discover solutions developed by engineers working on similar problems.

Field Visits

Engineers look to build from previous experiences and technologies to solve current problems. To help refine their solutions, engineers often visit locations using similar technologies or locations developing products that may be helpful to solving the engineering challenge they face. Engineers can improve their knowledge about technologies and solutions by seeing the technologies in action.

Engineering Research in History

Engineering research leads to many different inventions and innovations. The US government funds research in many different settings, including universities and independent contractors. One of the main research centers is the National Aeronautical Space Administration (NASA). You know that NASA has flown into outer space and landed on the moon, but did you know their engineering research has led to some of the items you use every day? NASA engineers have developed many technologies for space travel that have been adapted for everyday use on earth. Listed below are some of the most notable NASA engineering discoveries.

- **Invisible braces.** The plastic used for invisible braces is called translucent polycrystalline alumina (TPA). TPA was developed to protect infrared antennae from heat-seeking missile trackers. It was found that TPA was strong enough to withstand use in the mouth, while still being lightweight and clear.
- **Scratch-resistant lenses.** The material used to coat the eyeglass lenses that you wear was originally developed to coat the visors of astronauts. See **Figure A**.


Figure A.
Artem Illarionov/Shutterstock.com

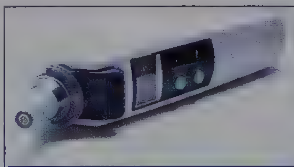
Figure B.
Tina Rencelj/Shutterstock.com


Figure C.
Nyvit-art/Shutterstock.com

- **Digital ear thermometer.** The development of the digital ear thermometer is based on the creation of NASA technology to measure the temperature of stars with infrared technology. See **Figure B**.
- **Cordless tools.** During the 1960s space missions, NASA engineers realized they needed a cordless tool to use in space. Along with Black & Decker, engineers created the battery-powered motor drill, which is the predecessor to the cordless hand tools used today. See **Figure C**.
- **Water filtration.** NASA engineers developed and refined the use of charcoal for water filtration to ensure their astronauts had clean drinking water while they were in space. This technology is still used today in the water filter you may have in your refrigerator.

For example, a manufacturing engineer may be developing a solution to improve the efficiency of a manufacturing firm that produces pieces of economical furniture for distribution to a major chain retail store. The engineer will look at different ways to improve efficiency and make multiple field visits to different locations to view how other engineers have solved this challenge. Included in the engineer's visits may be other furniture factories with similar assembly lines to improve their own assembly line's efficiency. Also, the engineer may visit manufacturing businesses that manufacture products other than furniture, to look at their manufacturing distribution arrangement. See **Figure 4-12**.

Engineers will also visit the location where the solution will be used. Engineers can gain great insight into a product through an analysis of the environment in which the product is used. For example, mechanical engineers developing new technologies to improve the land excavating process will visit work sites to see how their backhoes and other excavating equipment are used. See **Figure 4-13**. These visits may be for one small component of a tool or for a complete redesign of the tool.

Figure 4-13.

Field visits may include current work sites, where engineers can see how equipment is being used.

majeczka/Shutterstock.com

Figure 4-12.

An automotive assembly line is an example of a site an engineer may choose to visit while conducting research on a potential solution.

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Discussions with Others

Along with field visits, engineers also talk with people involved with the technologies in which they are working. These people may be fellow engineers, designers, production technicians, users of the technology, salespersons, or any other individuals connected with the technology. These discussions may take place as part of a field visit, or these contacts may be made as formal interviews, focus groups, or informal discussions. Also, online discussions are increasingly popular among engineers. Some websites include areas for online discussion. A ***discussion forum*** is an area on the Internet where a person can type a question or comment and other people can answer the question or comment on the original message. Discussion forums are used by engineers working on similar problems. Many times an informal discussion with a user of a specific product leads engineers to redesign the product.

Discussions with engineers take place in many different formats. One example is two engineers working together to solve a problem. An electrical engineer may be working on a new electronic control for a highly complex automotive system. The engineer may contact mechanical engineers to gain a better understanding of the mechanical tools the system will be controlling and the history of the mechanical systems. Also, the engineer will likely discuss this product with other electrical engineers who have worked with similar problems. See **Figure 4-14**. The engineer will keep detailed notes for future reference in the engineering notebook about the discussions.

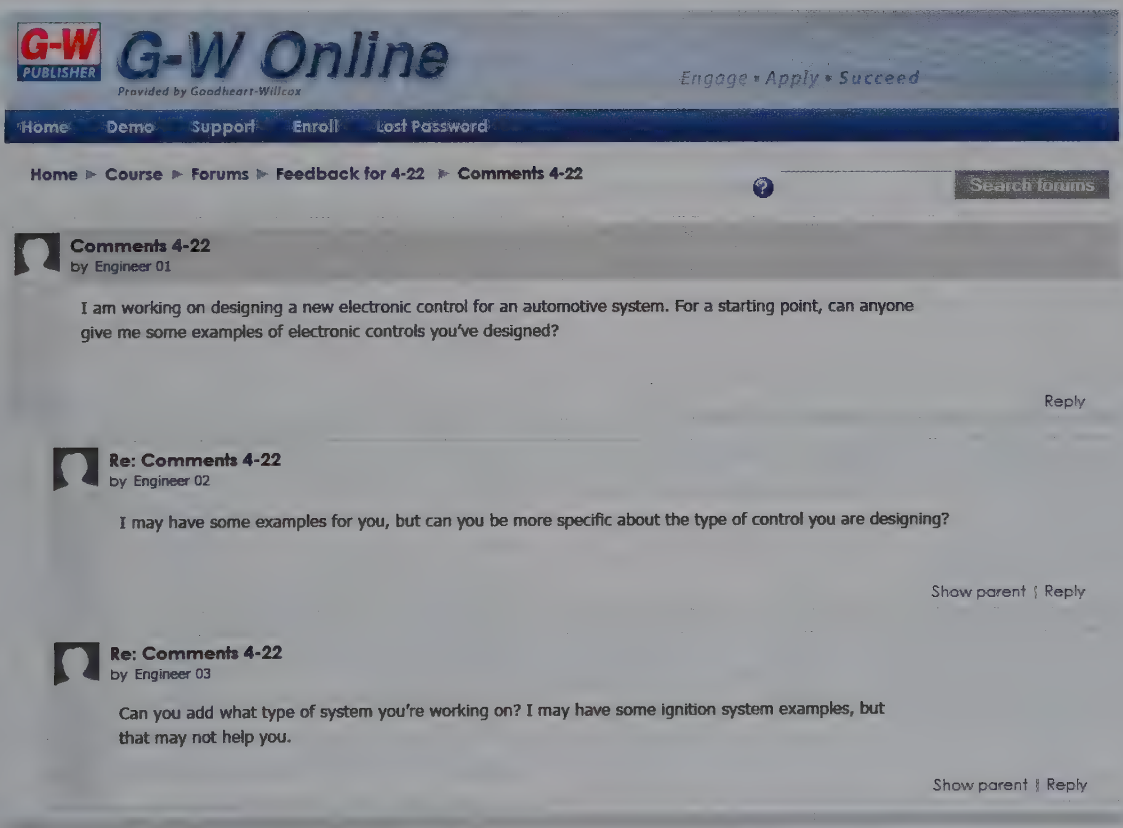

Figure 4-14.

Engineers often discuss potential solutions and products with other engineers who have worked with similar problems.

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Experimental Research

Engineers must also perform experimental research to help develop their solutions to engineering design challenges. ***Experimental research*** is a type of research that uses tests to discover information about your potential solution. The type of experimental research typically conducted by engineers depends heavily on which type of engineering field they work and the specific problem they are attempting to solve. Engineers in different disciplines perform different types of experimental research from one another, but there are few considerations all engineers are interested in discovering through experimental research: material properties, feasibility, production possibilities, and effectiveness.

Material Testing

Materials are critical to any engineered product. Materials have specific properties that must be considered when producing a product. Specific material properties can be discovered through library research, but there often needs to be an experiment to determine if the material is appropriate for a specific solution. Materials have specific properties that are mechanical, electrical, chemical, thermal, magnetic, acoustical, environmental, optical, atomic, and radiological. Material properties are discussed in detail in Chapter 7.

Engineers research the ratings of each of the material properties through library research, but they often perform experiments either through digital simulation or physical experiments to determine a material's appropriateness for a specific application. These simulations are discussed in Chapter 6.

Feasibility Study

Feasibility is considered by engineers at many points throughout the engineering design process, but it is most important during the research stages of the design process. Feasibility is the potential for something to be practically completed. Once the engineers have brainstormed solutions and performed historical research, they must also consider the feasibility of the solution. In general, ***cost feasibility*** is an evaluation of the effectiveness of the potential solution from a financial perspective. Estimates for the cost of the materials, production, and logistics of the product are considered to determine if the product is worth the financial and time costs to the company producing the product.

For example, an engineer may be designing a cup that needs to be strong enough to survive a 4′ drop without breaking and still be useful. The engineer would look over the properties of various materials to find a strong material. While the engineer could select to use steel over plastic, it would not be very cost effective to have the material made from steel because of the cost of materials and labor. The engineer may select a plastic material because of the potential cost to the company and consumer.

Production Research

Engineers must consider the possibility of producing a solution during the research stages of the engineering design process. Engineers experiment with the ways different solutions will go from design idea to a produced product. Production costs must be minimal, and engineers always look for the simplest solution for a problem. Along with material selection, engineers analyze how the material will be turned into the final product. Because engineers use science and technology to produce an actual solution, they must consider the realistic possibilities of producing the product. Key to this process is performing experiments while taking constraints into consideration. For example, aerospace engineers face many challenges with the weight of materials. During the research stages of engineering design, engineers make sure they have the appropriate materials and production techniques available to complete the potential solution. See **Figure 4-15**.

Another example is the development of new components for an automobile. Mechanical engineers may be faced with a challenge to develop a new braking system for an automobile, but it needs to be able to be produced with the current equipment and assembly line personnel. The engineers working on this challenge must consider how their design fits into the current production possibilities of the automotive facility.

Figure 4-15.
Engineers consider the capabilities of their CNC equipment to manufacture a specific product.

Lisa S./Shutterstock.com

Effectiveness Research

Effectiveness is the level at which an engineer's design meets the intended outcome or effect. One use of experimental research is to determine if the idea will work with all of the considerations of production, cost effectiveness, and use of specific materials. Engineers will perform experiments to determine if the basic idea will work. These early experiments do not always use the actual materials anticipated in the design, but they may use models to illustrate the idea while the research and other experiments provide information on the materials, cost efficiency, and production possibilities.

Structural engineers may produce a model bridge to test the effectiveness of their design. By using scaled materials and the appropriate scaled weight, they can simulate the effectiveness of the bridge through an experiment. Chemical engineers may test combinations of different chemicals to produce a new type of lubricating fluid for a hydraulic chamber. At this stage, the chemical engineer may make sure the chemicals will bond together as anticipated so the solution can be developed further. The tests this early in the engineering design process are typically designed to ensure the idea is a real and workable potential solution to the problem.

Trade-Offs

Once the engineers have performed the initial historical and experimental research for potential solutions, they begin the solution creation step. The engineers begin by analyzing the advantages and disadvantages of each approach. Each solution will have good and bad components and it is the job of the engineer to consider all of these strengths and weaknesses to determine which of the designs will be most beneficial. The engineer performs a trade-off analysis by looking at all the strengths and weaknesses of each design.

A ***trade-off*** is the consideration that gaining one positive quality in a design means you lose one other quality. This compromise is a challenge for engineers to determine the best solution. Engineers use a trade-off chart to analyze the potential trade-offs of each solution. The trade-off chart is different for each problem, but there are similarities among all charts. Each chart lists different characteristics important for the design and the engineer rates the appropriateness of each quality to the overall design solution. The trade-off chart provides the engineer with a way to measure which design is the best fit for the problem. Common considerations for the chart are listed on the next page but can be different with each

problem because of the different constraints and criteria for each design.

- **Economic feasibility.** Is it cost effective?
- **Ease of production.** Can the product be produced effectively?
- **Appearance.** Does the product look good?
- **Maintenance.** Is the product easy to maintain?
- **Marketability.** Is the product marketable?
- **Convenience.** Is the solution convenient for the user?
- **Greenness.** Does the product have a negative impact on the environment?
- **Multiple uses.** Does the product solve multiple problems?

The sample matrix shown in **Figure 4-16** could be used by an engineer to determine the best way to move people from home to work to improve rush hour road congestion. As you can see, you give points (positive, negative, or neutral) for each idea under each category. You then total the points in the final column.

Engineers also consider the criteria and constraints of the initial problem when analyzing the trade-off matrix. As previously discussed, a constraint is a specific condition that limits the engineering design solution. A criteria is a rule or principle that is used as a basis of an engineering design problem. The constraints and criteria drive the engineering design process and are revisited when analyzing the trade-offs to make sure specific design components do not ignore the specific constraints and criteria required for the design.

Selecting the Best Approach

Once the engineers have gathered all of the necessary information from their research, it is time to analyze the data to make the final selection. Sometimes engineers have one solution that is clearly better than the other designs, but this is not always the case. It is important for engineers to rely on members of their design team and to effectively communicate their design to those interested in the engineering process. Those interested in the design may be project managers, customers, consumers, engineers, and many other potential stakeholders.

Analyze Data

Depending on the specific type of problem the engineers are solving, there may be many different people involved in the data analysis process. Members of large engineering design teams may need to present their ideas to others on their team, along with presentations from the other teammates, **Figure 4-17**. In other cases, the engineer may be a team of one person that needs to present the idea to their customer or the product manufacturer. In either case, documentation of the initial designs is critical to communicating the research findings.

Sample Trade-Off Matrix

Solution	Train	Monorail	Bus	Commuter cars
Appearance	0	+1	0	+1
Manufacturability	+1	0	+2	+2
Feasibility	+1	0	+1	–1
Low maintenance	0	+1	–1	–1
Marketability	+1	+1	0	+1
Environmentally Friendly	+1	+2	0	–1
Total	4	5	2	1

Figure 4-16.

This sample matrix shows how engineers compare different potential solutions.

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Figure 4-17.
A structural engineering design team analyzes data and looks over possible solutions.

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The engineer's notebook is a record of all the different analysis performed through the engineering design process. By accurately recording the research, the engineer can look over the data and reach a conclusion on the best approach to solving the problem. Some potential ideas will clearly not work after analysis of the different research methods. However, engineers typically have to choose between multiple solutions that may work to solve the problem.

To help make these selections, engineers look at the preferences of the design ideas. Preferences are desirable, but optional, components of the final solutions. While there may be multiple solutions that meet the constraints and criteria, the engineer may have some preferences that are met by specific designs. These preferences may also be developed by the project manager or customer. Engineers must ensure preferences do not take away from the effectiveness of the product. However, some preferences fit into the best design.

For example, a computer engineer may be developing a new processor that will speed up the productivity of a personal computer. The engineering design team develops three new processors designed to speed up access and processes on the computer and will not cost more to produce than the processors currently used. One of the new processors also uses significantly less energy than the other new designs. The preference of one design being more energy efficient is not a requirement, but it helps the engineers select the new design because of the "free" feature of energy efficiency the design provides.

Final Selection

Taking into consideration the research, tradeoff chart and all of the preferences of designers and stakeholders, the engineer or engineering design team makes the selection of the design to take into development. This selection cannot be seen as final. Engineers realize with further design and analysis they may need to revisit some of their previous ideas if their selected solution does not work effectively once it is modeled and further analyzed.

The engineering notebook is critical for further development of the solutions. With records of all the initial research into this solution, engineers will be able to revisit information about

other designs and make possible adjustments to their selected approach. Redesign is critical to engineering design and must be available at all stages to reach the optimal solution.

Once the final design is selected, engineers develop more detailed sketches for use in communicating their ideas and as a way to advance to the design, modeling, and analysis steps discussed in the next chapters. To accomplish these detailed sketches, engineers develop refined sketches. The ***refined sketches*** combine all the components of the final design, which may be a combination of different ideas. The refined sketches have much more detail than rough sketches and are used as a framework for further development. Refined sketches are usually a series of sketches detailing all of the different systems in the engineered design.

For example, a rough sketch for a new bicycle design could be one sketch of the overall bicycle with little information about each system included. Once you select your idea, refined sketches include drawings of each system, such as gearing, pedals, and steering, and may be a series of drawings. These drawings, while still created by hand, will have a new level of detail needed to begin modeling the solution.

Going Green

Hybrid Vehicles

Engineers are constantly trying to develop solutions to problems encountered on a daily basis. As we discovered in this chapter, engineers must be dedicated to using many different forms of research to find potential solutions. Solutions are developed by using different types of research over a long period of time. Much of the research currently being conducted is focused on redeveloping more environmentally friendly solutions to existing problems.

One example of this type of innovation through research is the hybrid vehicle. The following is a brief time line of the development of hybrid vehicles:

- 1839—First electric car is developed by Robert Anderson of Aberdeen.
- Late 1800s—Battery technology is drastically improved by many researchers and engineers.
- 1900—The Ferdinand Porsche Company develops a vehicle that uses an internal combustion engine to power a generator to recharge batteries making it the first hybrid vehicle. The vehicle travels 40 miles on the battery alone.
- 1916–1917—Two hybrid vehicles are introduced by Baker and Woods. Both vehicles work but do not have as much power as vehicles powered by an internal combustion engine.
- 1970s—Victor Wouk, an electrical engineer, researches and develops models for hybrid vehicles including a prototype based on a Buick Skylark.
- 1989—Audi introduces the Audi Duo, a vehicle that uses an internal combustion engine and an electric generator to power the automobile.
- 1997— Toyota introduces the Toyota Prius, the first widely available hybrid vehicle, **Figure A**.

Figure A.

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Summary

- After brainstorming, engineers work on sketching and researching the potential design solutions.
- Engineers communicate their initial design solutions using rough sketches.
- The four basic steps of sketching are to visualize, block out, outline, and detail solutions.
- Engineers begin sketching by visualizing the appearance and functionality of the object.
- Once the visualization of the object is developed, it must be blocked out using a combination of boxes, cylinders, cones, and pyramids.
- After blocking out shapes, solutions are outlined before feature details are added.
- Two types of research are historical research and experimental research.
- Historical research involves library research, field visits, and discussions with others. Engineers use library research to look at how they can adapt current technologies and tools to solve the problem at hand.
- Engineers use experimental research to discover information relating to material properties, feasibility, production possibilities, and effectiveness.
- After the initial research has been completed, engineers consider the strengths and weaknesses of each solution. A trade-off analysis helps engineers determine which design will be most beneficial.
- Engineers also consider the criteria and constraints of the initial problem when analyzing the trade-off matrix.
- To make the final selection of the potential solutions, engineers analyze the data from the research, assess preferences, and consider the trade-offs.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

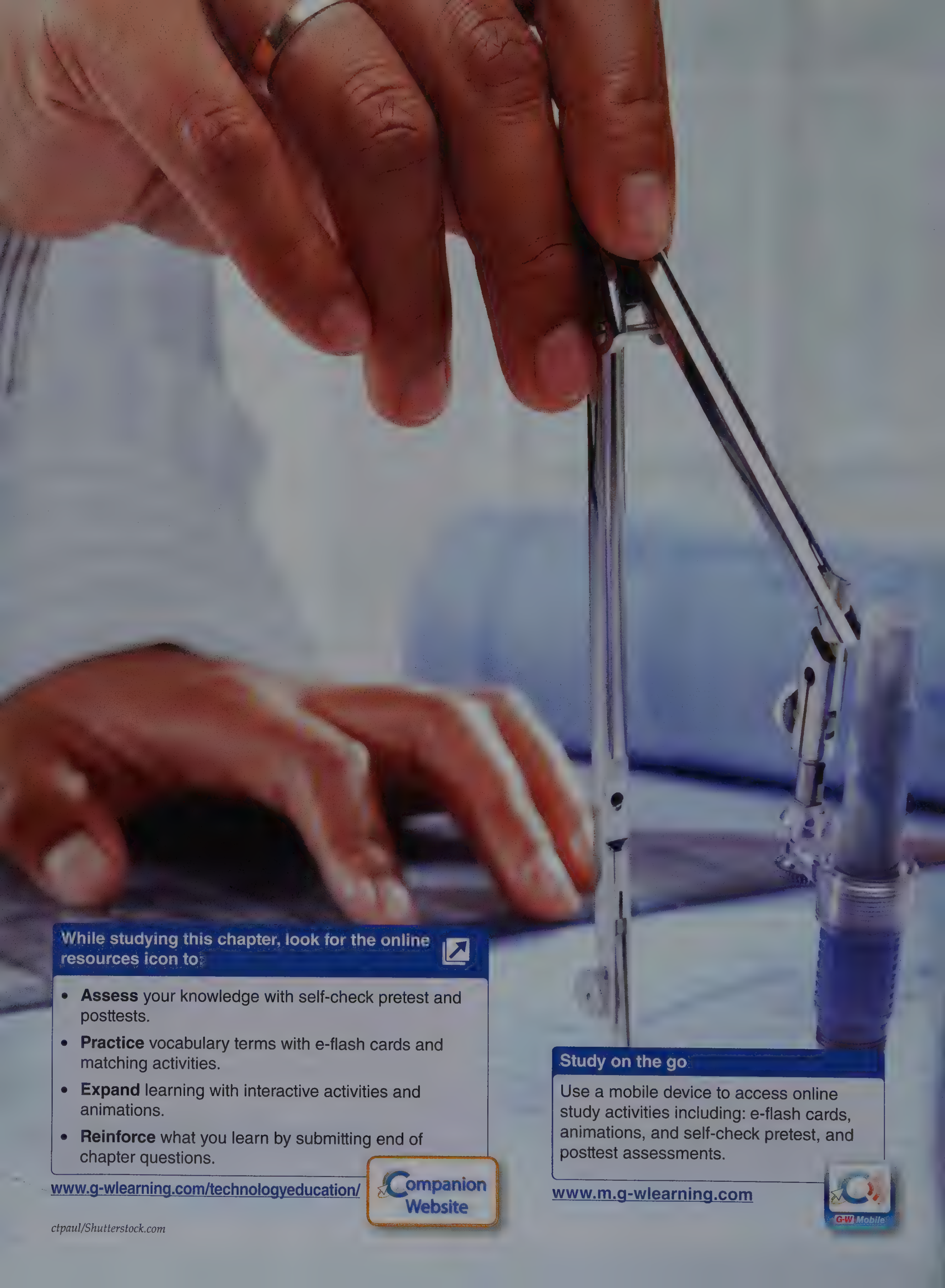
Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is research?
2. When are rough sketches normally developed?
3. In the _____ step of the sketching process, the engineer is concerned with the appearance and functionality of the object.
   A. visualization
   B. blocking out
   C. outlining
   D. detailing
4. The _____ is the basic shape of the object.
5. Library research is a type of _____ research.
6. Which method of research involves engineers seeing technologies in action?
   A. Library research.
   B. Discussion forums.
   C. Field visit.
   D. Experimental research.
7. What four considerations are engineers interested in when performing experimental research?
8. When is a potential solution's feasibility considered most important?
9. Engineers analyze a solution's _____ by looking at the advantages and disadvantages to create a chart.
10. _____ sketches combine all the components of the final design.

Reinforce learning



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- **Assess** your knowledge with self-check pretest and posttests.
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Chapter 5

Communicating Solutions

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Key Terms

- assembly drawing
- detail drawing
- dimensioning
- engineering drawing
- leader
- location dimension
- oblique drawing
- perspective drawing
- schematic drawing
- shape dimension
- size dimension
- working drawing

Practice *vocabulary*

Objectives

After studying this chapter, you should be able to:

- Explain the importance of properly communicating design solutions.
- Identify three types of working drawings.
- Describe different drawing classifications.
- Select and use appropriate symbols.
- Identify line types used in drawings.
- Describe dimensioning guidelines.
- Discuss industry guidelines used in communicating design solutions.

History of Drafting

A drafter is someone who draws documents for official purposes. Drafters are among the oldest documented professions.

Drafting began with prehistoric humans drawing images on the walls of their caves to communicate their ideas and representations of the world around them. The first known cave paintings are from Aurignac and were drawn thousands of years ago. Drafters have used many different tools over the years such as rocks, sticks, pencils, T squares, compasses, and now modern CAD software. While the technologies have drastically changed, the basic principle has remained the same. Engineers and drafters communicate their design ideas with others to produce solutions to the problems they encounter. See **Figure A**.

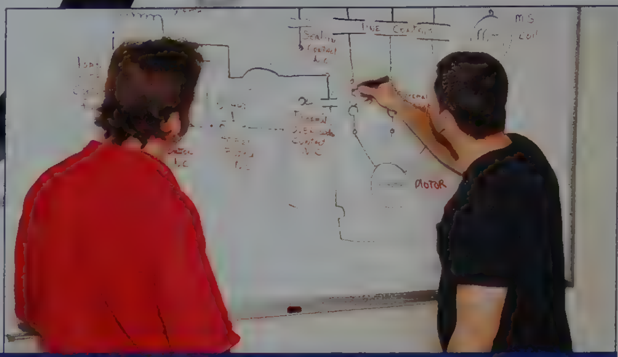

Figure A.

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Once engineers complete their initial research of designs, they begin to create solutions to solve their problems. You have learned that the solution creation step includes analyzing design solutions and choosing solutions. The final step in creating solutions is to communicate the solution. See **Figure 5-1**. Engineers use different types of drawings to further design their initial brainstorming ideas. In this chapter, different types of engineering drawings used to illustrate design solutions are described. This chapter shows the different types of drawing methods used by engineers. Engineers must select the appropriate drawing approach to ensure their designs are clear to managers, fellow design team members, and customers.

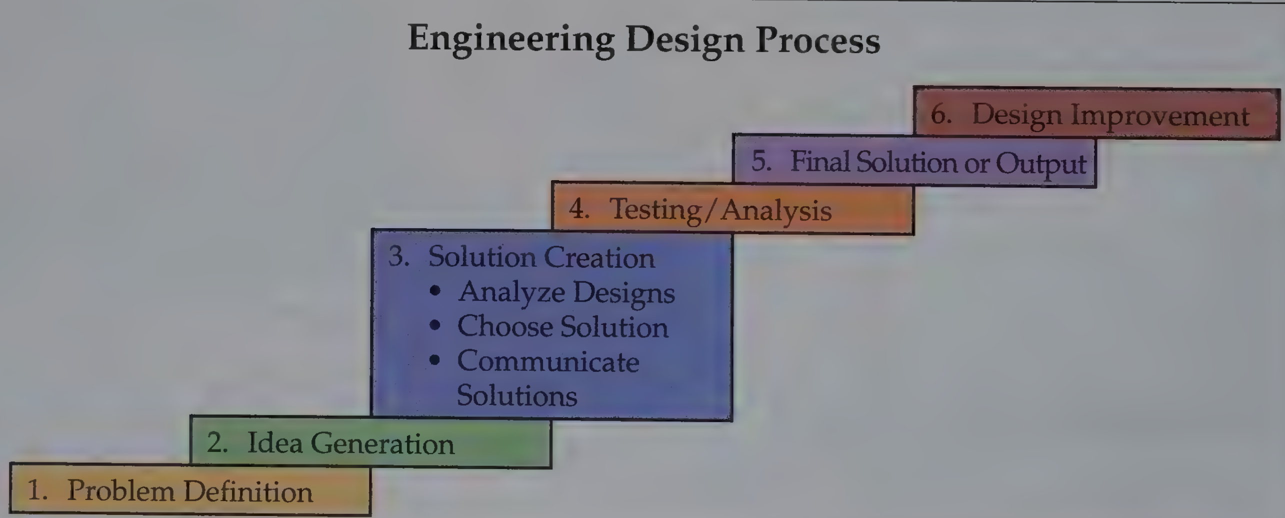

Figure 5-1.

Following analyzing and choosing design solutions, communicating solutions is the final step in solution creation.

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Engineering Drawings

Engineers use drawings to further develop and communicate their designs. ***Engineering drawings*** are created to communicate products that will be manufactured. As you will see in future chapters, there are different engineering disciplines that develop different types of products, but all engineers rely on engineering drawings to move their designs into production.

Working Drawings

Engineers develop working drawings. ***Working drawings*** are engineering drawings that are the most complete drawings produced. Unlike rough and detailed sketches, discussed in Chapters 3 and 4, working drawings are extremely detailed and must be developed following strict standards. Most engineers follow the standards set forth by the American National Standards Institute (ANSI) to develop working drawings. By following specific guidelines, engineers can ensure their designs are understood by other engineers and manufacturers of their designs. Depending on the specific engineering discipline, the engineer uses a combination of three specific types of working drawings: detailed drawings, assembly drawings, and schematic drawings.

Detail Drawings

Engineers use ***detail drawings*** to show the exact shape and size of an object. The drawings show multiple views of the object to give an overall image of the object. Engineers select the views that provide the most detail for their designs.

Detail drawings provide enough information to produce the product. This information varies between products. Detail drawings include dimensions for all parts of the product to show the overall size and shape, along with detailed features of the product. Detail drawings often include notes to better describe the object to engineers and manufacturers. See **Figure 5-2**.

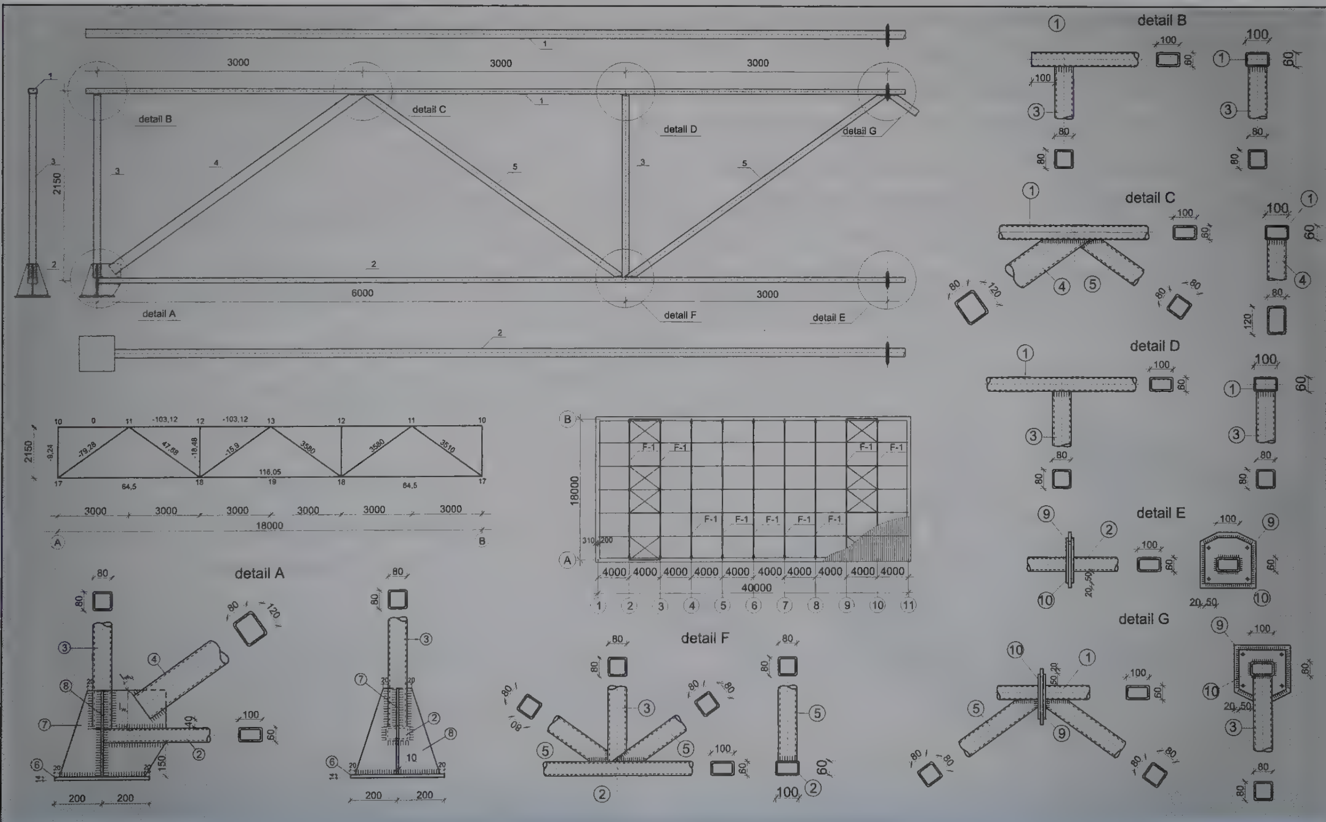

Figure 5-2.

Detail drawings include dimensions and notes to help engineers and manufacturers better understand the design.

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Assembly Drawings

Assembly drawings show how different parts fit together to create the entire object. Also known as exploded view drawings, assembly drawings show the relationships between different objects. Engineers use these drawings to simplify their designs and allow others to visualize how the different parts work together. You have seen assembly drawings when you put together a piece of furniture or work on a car. These drawings provide a guide for assembly and disassembly of a product. See **Figure 5-3**. Assembly drawings are drawn in three dimensions but do not show the sizes, or dimensions, of the components. If dimensions are needed for production, manufacturers look at the detail drawings previously discussed.

Schematic Drawings

Engineers use schematic drawings to show an entire system. ***Schematic drawings*** are used to show how different parts are connected together to form a system. Schematic drawings are most commonly used for plumbing systems, electrical circuits, and production lines. The purpose of a schematic drawing is not to communicate size or shape of an object, but to show how parts of a system work together. Dimensions are not used on a schematic drawing.

For example, electrical schematic drawings show the flow of electricity between different parts of the circuit, and plumbing schematic drawings show the way water flows through all of the different components of a water system. These drawings are intended to show the relationship between all the components in the system. They are often helpful in diagnosing a system problem because they describe the direction of flow and purpose of each object in the system.

The use of symbols is critical to the creation of schematic drawings. See **Figure 5-4**. Engineers follow the ANSI system of symbols. The engineer uses ANSI symbols for each part of the system and lines to connect each part of the system.

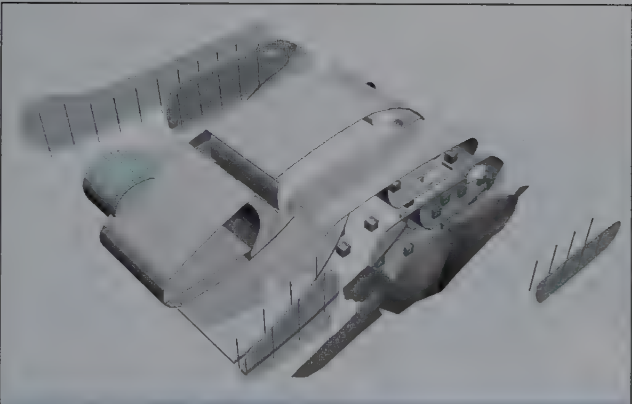

Figure 5-3.

This computer-generated assembly drawing shows how the product fits together.

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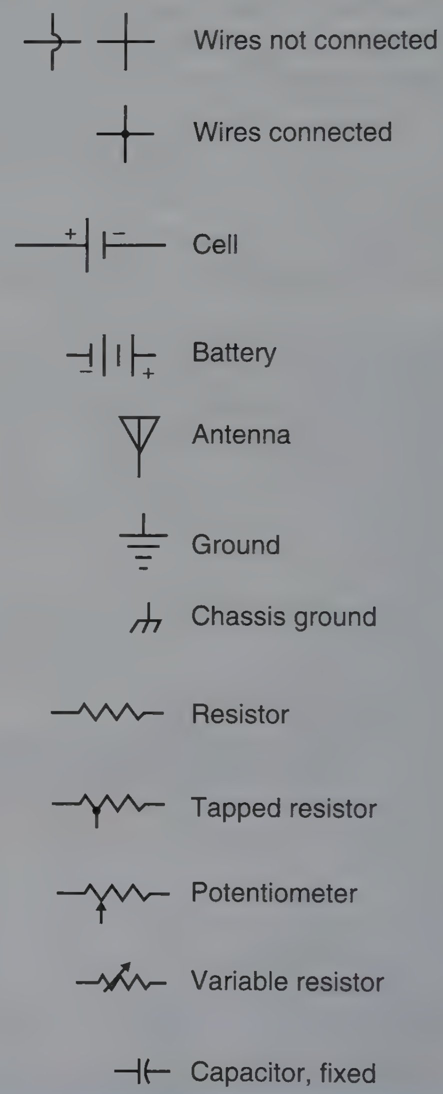

Figure 5-4.

Standard symbols are used to make schematic drawings easier to draw and understand.

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The lines are used to represent the path. For example, on an electrical circuit, the lines stand for wire, and in a plumbing system, the lines represent the pipe through which the water travels. See **Figure 5-5**.

Drawing Classifications

As previously described, engineers use various working drawings to show how a part is put together or to show the specific parts of a design. These drawings comprise two types of drawings: orthographic drawings and pictorial drawings.

Orthographic Drawings

Orthographic drawings use multiple views to describe the size and shape of an object. Because these drawings show many different views, they are often referred to as *multiview drawings*. Any three-dimensional object has six sides that can be illustrated. Engineers can use any combination of these six sides to illustrate an object. Engineers must select the best views to communicate their designs. Many times, engineers will use 3-D modeling software (discussed in Chapter 6) to create a model and then create orthographic drawings from their overall design to communicate their solution to production staff.

Orthographic drawings can be detail drawings when they contain all the appropriate information. However, not all orthographic drawings are detail drawings. Orthographic drawings are often developed as a rough sketch used to show the overall view of the object. They may not include all the information from a detail sketch.

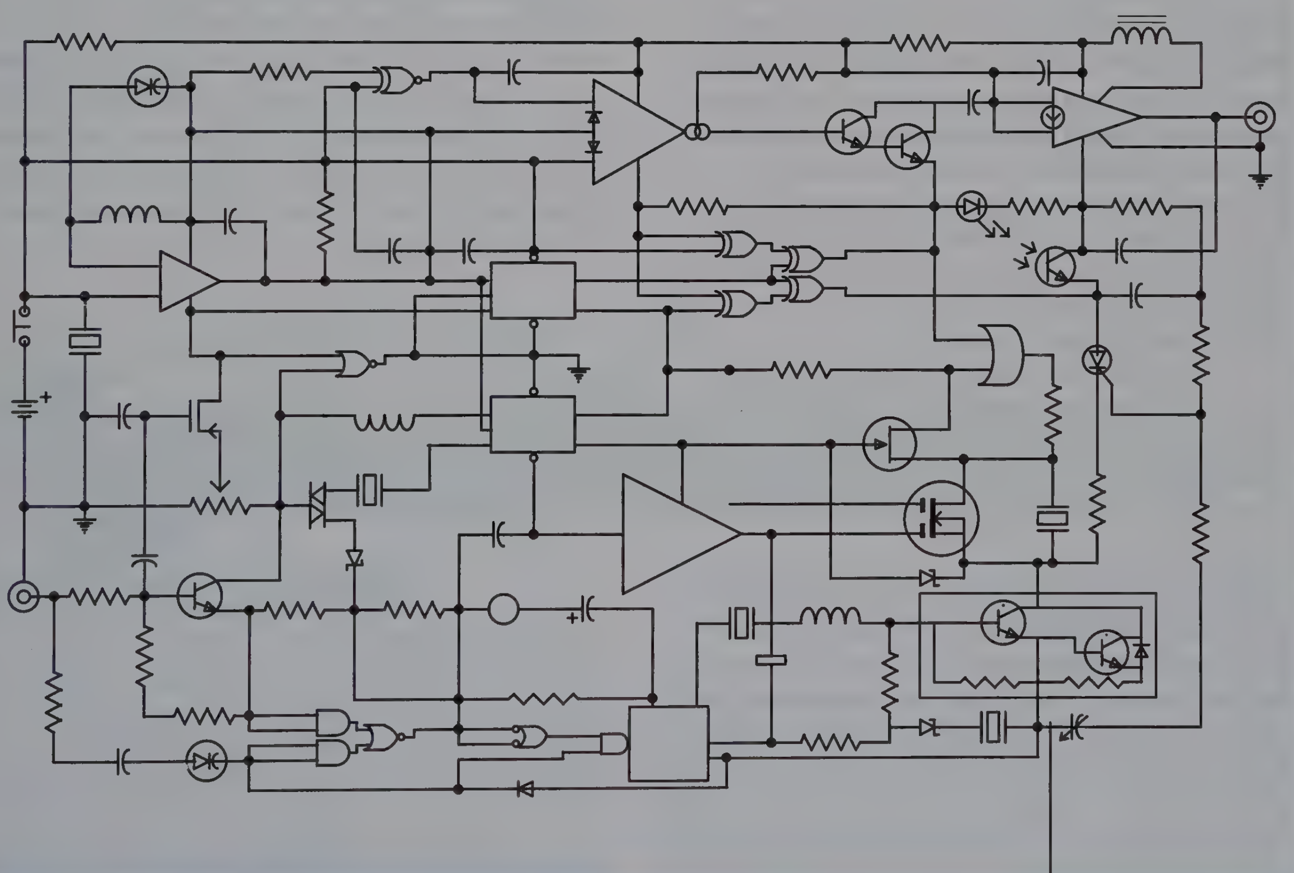

Figure 5-5.

Schematic drawings are used to communicate electrical circuits or plumbing systems.

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States of Matter

Matter can exist in various states. The most common states of matter are solid, liquid, gas, and plasma.

Solid matter is not flexible in its shape, nor in its size or volume. The particles that make up a solid hold more tightly to one another than particles of other states of matter.

Liquids have flexible shape. A liquid's particles are not woven together as tightly as those in a solid, resulting in flexibility. Any given amount of liquid remains the same no matter what type of container it is put into. Liquid will conform to the shape of its container.

Gas particles do not hold together, making it a free-form state of matter. It is more flexible than liquid because it can spread to the limits of its container, rather than just taking its shape. The volume of gas is not fixed. It spreads throughout a container, so its volume matches that of the container.

The qualities of the plasma state make it similar to the gaseous state. Plasma expands to fill the space in which it is contained. However, plasma particles are electrically charged. Plasma can be found in plasma televisions.

Matter can also change states. For example, water is a liquid. However, it can be frozen into a solid state, or it can be heated into steam, or a gaseous state.

Orthographic drawings are created using orthographic projection. Orthographic projection can be confusing to understand. The key to understanding orthographic projection is the ability to visualize the product. Visualization is the ability to mentally see a representation of a product for which there is no physical object. Engineers must have the ability to visualize objects. Engineers use orthographic projection to describe their visualization of a solution.

Orthographic projection can have up to six different sides, as in the case with rectangles. See **Figure 5-6**. Every rectangular object has four sides, top, and bottom. Each side becomes a different view. Orthographic drawings illustrate specific sides of an object. For example, when you look at a car from the front, you see the front bumper, headlights, windshield, side mirrors, and many other details. How does the view change when you look at the car from the side? On the side of the car, you see the front fender, driver side door, rear passenger door, rear fender, and small door that covers the gas cap. When you move to the rear of the car, what do you see? You see the rear bumper, taillights, back end of the trunk, rear windshield, and side mirrors sticking out from the sides of the car. If you crawl underneath a car, what do you see? You see the many different components that make the automobile move. You will see suspension systems, the engine, transmission, exhaust system, and many other objects. If you look at the car while standing above it, you see the top of the hood, passenger cabin, trunk, and side mirrors sticking out from the sides of the car.

To accurately describe the car, you need information from all of these views. This information includes the height of the car from the side, front, or rear; the width of the car from the top, front, or rear; and the overall length of the car from the top, bottom, or side.

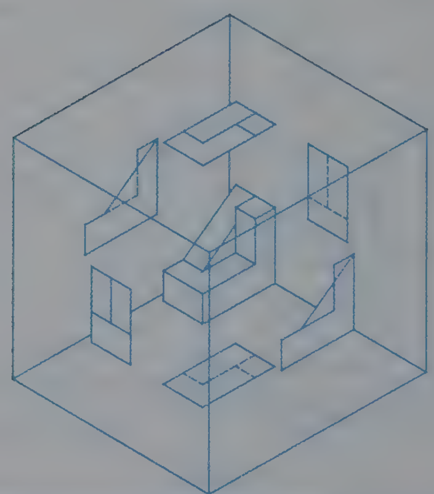

Figure 5-6.

The views of the object are projected onto the sides of a box.

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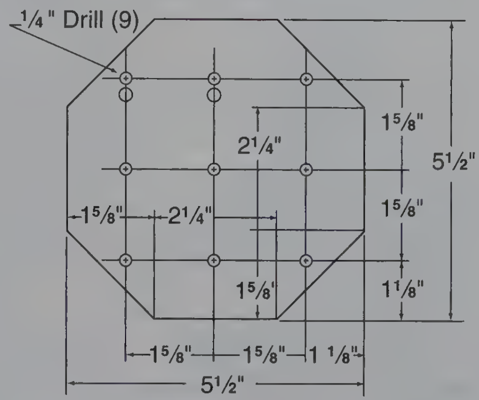
While a car is a complex machine, basic shapes also need information from all the sides to determine the overall size of the object and features on each side. Depending on the object, engineers may use any number of views to communicate their designs. Most commonly, engineers select a one-view drawing, two-view drawing, or three-view drawing.

One-View Drawings

One-view drawings are used to show flat pieces. Usually, these flat pieces have a standard or predetermined thickness. Creating solutions using materials such as hardboard or sheet metal are often displayed using a one-view drawing because all of the details of the object are usually present on one side of the object. The top view is most commonly illustrated in one-view drawings. See **Figure 5-7**.

Engineers design many projects that use one-view drawings. When engineers create a flat object, such as gaskets, flat plates, or sheet metal parts, they use one-view drawings. Manufacturing engineers also commonly use one-view drawings to communicate the details of a sheet metal stamp for the production of a specific part.



¼" THK PLATE

One-View Drawing

Figure 5-7.

This one-view drawing shows a flat object.

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Two-View Drawings

Engineers use two-view drawings to show cylindrical objects and objects with a round shape. Cylindrical objects are usually shown in two-view drawings and include one view that is a circle and one view with the details from the side of an object. To use a two-view drawing,

Going Green

Paper Recycling

While the process and guidelines have remained similar, the tools engineers use have drastically changed during the last 30 years from strictly pencil, paper, and drawing tools to the use of CAD software. Along with this advancement in computer design, some drawings may not be printed until they are ready to be produced. This has reduced the amount of paper copies of materials, but engineers and production staff still use paper copies to display for clients, take to field visits, and other uses. Using less paper is good for the environment.

Did you know that in past few years almost 60% of all paper used in the United States was reclaimed and recycled? Paper is made from cellulose, which is fiber found in trees. Engineers developed a method to take used paper, shred it up, and mix it with water to create pulp. This pulp is then refined and turned into slush. The slush is then mixed with different chemicals, such as dyes and other additives, and the water is drained. The pulp is ready to be processed. The pulp is then pressed between rollers to remove any moisture and then pressed onto rolls to be used in many different paper products.

the object must have consistent details around the shape, so it appears similar on all sides. Engineers can use two-view drawings to show the front, sides, top, or bottom of an object. See **Figure 5-8**.

Cylinders for engines are drawn using a two-view drawing. The top view of an engine cylinder will highlight the overall diameter of the cylinder and the side view shows the placement, size, and arrangement of the rings.

Three-View Drawings

Three-view drawings are most commonly used for rectangular objects. Traditionally, three-view drawings show the front, top, and side views of an object. Engineers use the front view to show the height of an object, the top view to show the thickness of the object, and the side view to show the width of the object. See **Figure 5-9**.

Complex designs require a three-view orthographic drawing. Brackets used to attach materials to a wall are communicated using a three-view drawing because of the different features on each side of the design. Also, products made from solid materials, such as a cylinder head on an engine, will feature three views. Structural engineers use three-view drawings to show the details and specifications for a support beam with holes to connect to another part of the structure.

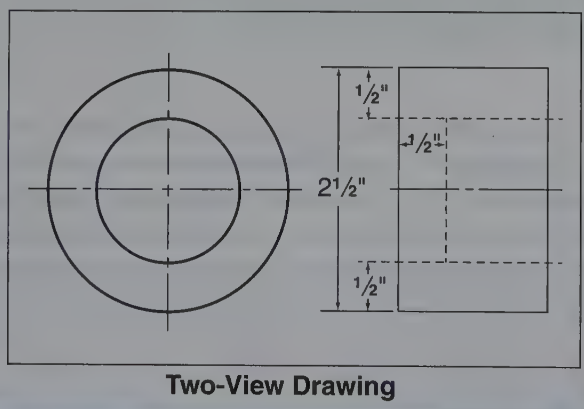

Figure 5-8.
This two-view drawing shows a round object.

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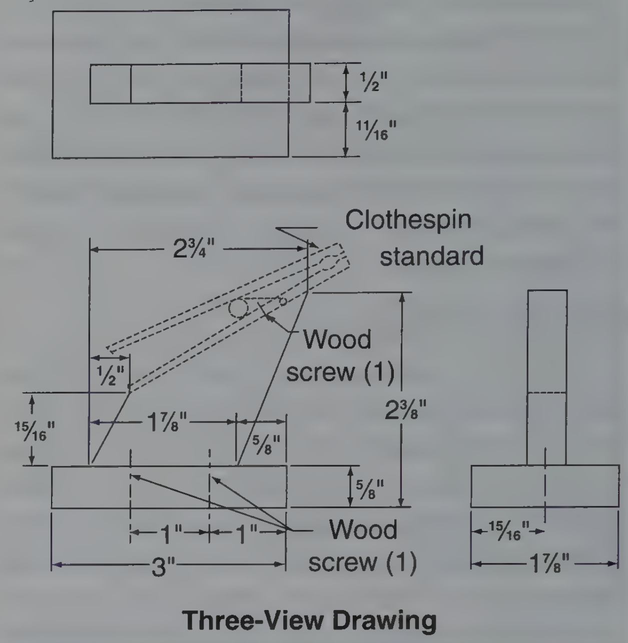

Figure 5-9.
This three-view drawing shows a rectangular object.

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Pictorial Drawings

Pictorial drawings show the object as it would appear to a person looking directly at the object. Pictorial drawings are like pictures. They are commonly used to communicate designs to people who do not understand or use orthographic drawings. Engineers use pictorial drawings to communicate designs to their customers or fellow designers. Pictorial drawings appear three-dimensional so they are easy to understand, and they give an overall view of the design. See **Figure 5-10**. The three types of pictorial drawings most commonly used by engineers are isometric drawings, oblique drawings, and perspective drawings.

Isometric Drawings

Isometric drawings are the most common type of pictorial drawing used. Isometric drawings use angles equal to each other and are always drawn using the same standard angles. The lines at the bottom of the object are always 30° from the baseline with the opposite corner 150° from the baseline. See **Figure 5-11**.

Figure 5-10.
Pictorial drawings are like pictures and are used to communicate designs to customers or fellow designers.

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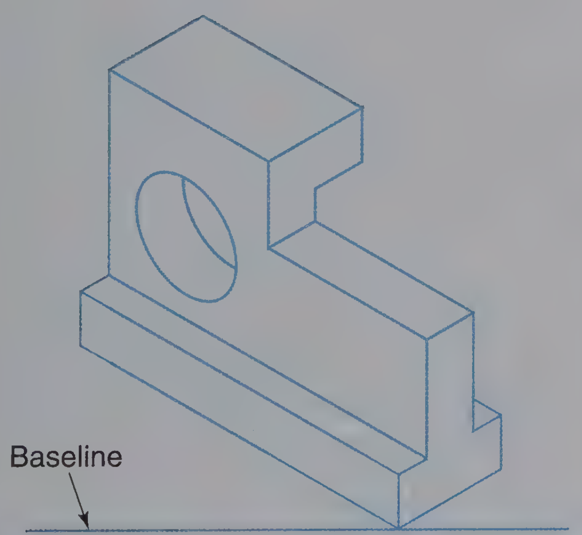

Figure 5-11.
Isometric drawings are created so the horizontal lines are 30° from the baseline.

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All lines in isometric drawings are drawn to scale, which means all the lines are drawn at the same proportion of the object. In brainstorming, a sketch size is not a critical concern, but in final isometric drawings, dimensions must be accurate.

Oblique Drawings

Engineers use oblique drawings to highlight one side of an object. ***Oblique drawings***, like isometric drawings, are drawn in 3-D, but instead of using a determined angle at the front of the image, the drawing features one side of the object as the front image. Oblique drawings are commonly used when the details of one side of the object are more important than those of the other sides. Engineers do not use these drawings as often as they use isometric drawings.

Engineers begin by drawing the front view at full size or to an appropriate scale, as it would be drawn in an orthographic drawing. Once the front view is completed, the engineer draws lines back at angles to provide depth to the object. The most common angles used for oblique drawings are 30° or 45°. Receding lines may be drawn to scale. See **Figure 5-12**.

Engineers commonly use oblique drawings for objects that feature a great amount of detail in the front view. One example use of an oblique drawing is when engineers want to show a new television design. They may want to communicate the look of the front of a computer to a customer who is not concerned with the appearance of

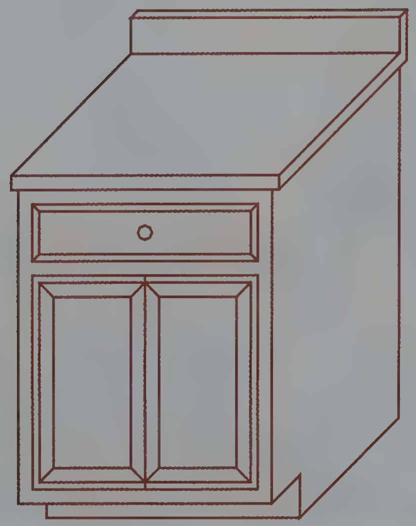

Figure 5-12.

Objects with most of the detail in the front view are often drawn with oblique drawings.

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the sides of the unit. Also, engineers may use an oblique drawing to show the details on the front of a new refrigerator design.

Perspective Drawings

Perspective drawings are used to show an object from a specific point of view. Perspective drawings simulate what the eye sees if looking at the object. The most unique part of a perspective drawing is the use of a vanishing point. A vanishing point is a spot at which receding lines converge. Engineers may choose to illustrate their designs using a one-point perspective, two-point perspective, or three-point perspective.

A one-point perspective drawing uses one vanishing point. One-point drawings look similar to oblique drawings because all of the angles are going to one location from the front image. One-point perspective drawings are different from an oblique drawing because the side lines go to a point instead of at a set angle from the front image.

Two-point perspective drawings are developed with an angle at the front of the drawing, like an isometric drawing, but instead of being drawn at set angles, the lines of both sides are drawn to a point. See **Figure 5-13**.

Three-point perspective drawings use three vanishing points: one located on each side and one located above the object. Three-point perspective drawings are not nearly as common as one- and two-point perspectives, but they are used by structural engineers on skyscrapers to show how the building will look from the ground looking up at the building.

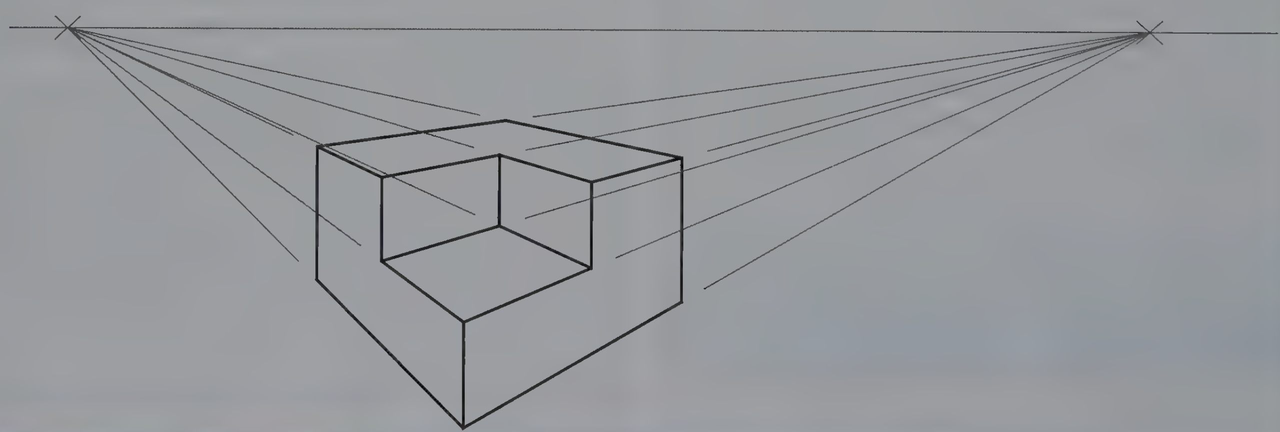

Figure 5-13.

This is an example of a two-point perspective drawing.

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Math

Triangles

The triangle theorem states that all interior angles of a triangle add up to 180°. We use the triangle theorem to identify the missing angles in a triangle using an algebraic equation. Look at the triangle in **Figure A**. We are given the angles for A and B, but we must find the interior angle for C.

$\angle A + \angle B + \angle C = 180°$

$30° + 90° + x = 180°$

$120° + x = 180°$

$x = 180° - 120°$

$x = 60°$

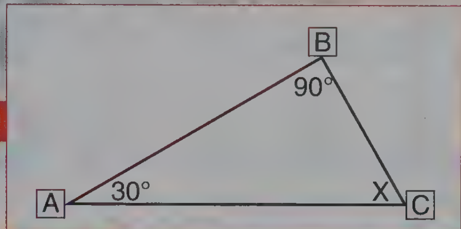

Figure A.

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For each of the problems below, two angles of a triangle are given. Use the algebraic equation and the triangle theorem to find the missing third angle.

1. 90°, 45°
2. 50°, 60°
3. 35°, 65°
4. 53°, 67°
5. 22°, 86°
6. 89°, 22°

Drawing Guidelines

In the previous sections of this chapter, we discussed the many different types of drawings engineers use to communicate their designs. Engineers must also follow standard methods and rules when creating these drawings to ensure their solutions are properly communicated to other members of the design team and the production staff who will produce the final product. Using proper techniques allows engineers from across the globe to interpret the drawings.

Symbols

Symbols are used to represent different entities in a drawing. As illustrated earlier in this chapter, symbols are regularly used in schematic drawings to represent different parts of an electronic or hydraulic circuit. In schematic drawings, the symbols represent a specific component of the circuit. Symbols are also used to inform engineers and production staff about different criteria required to produce a solution.

Symbols are used in engineering drawings to show the properties of a specific object. In technical drawings, engineers use symbols to illustrate the diameter of a specific part or to illustrate the center of an object. Each engineering discipline, discussed in later chapters, uses specific symbols to help communicate designs. Along with discipline-specific symbols, standard symbols are used across many different engineering disciplines. This section describes standard symbols used to create technical drawings across different engineering disciplines.

Many organizations develop symbols to use throughout the different engineering disciplines, but two major groups are ANSI and the International Organization for Standardization (ISO). The guidelines developed by ANSI and ISO are accepted by engineers worldwide.

Some ANSI symbols associated with schematic drawings were shown earlier in the chapter, but ANSI has developed many other symbols for other fields such as mechanical engineering and structural engineering. ISO provides symbols we use every day such as safety symbols. Sample safety symbols are shown in **Figure 5-14**.

Figure 5-14.

These safety symbols are used to help everyone understand warnings.

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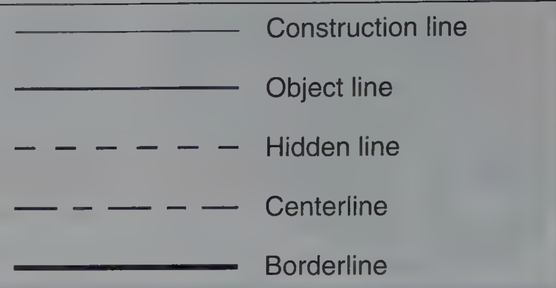

Figure 5-15.

These are the five primary lines used in a drawing.

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Line Types

When you view an engineering drawing, as shown in **Figure 5-15**, many different lines are visible. Engineers also use different line types in drawings to highlight different parts of a design and to show features that may not appear if you were to look at a 3-D model of the object. Each line type has its own characteristics, which are universally understood by engineers and manufacturers producing the objects. The five primary line types are construction lines, object lines, hidden lines, centerlines, and border lines.

Construction lines are lightly drawn lines used to lay out the drawing. They are not part of the object itself. They are merely used as reference points to help connect different pieces of the drawing. Construction lines are usually removed from the final drawing, and with the use of computer-aided drafting (CAD) software, they do not appear on the final print.

Object lines are heavy and dark lines used to show the edges of the object in the drawing. Object lines are the actual outline of the object and are the visible edges if you are viewing the 3-D model of the object.

Hidden lines are drawn with short dashes. Hidden lines are used to show parts of the drawing that are hidden from sight in the view that is drawn. Hidden lines may be used to show details that are cut out of the bottom of an object and lines that may be visible when you look at the object from another view.

Centerlines are drawn using alternating short and long dashes. Centerlines are used to show the center point of an object. Engineers need to show the center points of many objects including circles, arcs, and ellipses.

Border lines are the thickest and darkest lines in a drawing. Border lines are used to create a border around the edges of the paper.

Scale

Drawings may be drawn at full scale, which means all lines on the paper are identical to the size of the actual product. Full scale means 1″ = 1″ (or 1:1). Full scale should be used if the object will fit on the paper; if not, you may use a different scale.

Using a different scale typically reduces the lines of the drawing so the object fits on the paper but remains proportionally correct. You can draw the product so that every 1/2″ on the paper equals 1″ on the actual product. This is called 1/2″ = 1″ scale (or 1:2). Some common scales include 1/2″ = 1′ and 3/8″ = 1′. You may use other scales as well if your object will not fit onto the paper or if it will be too small to see on the paper. See **Figure 5-16**. Scale is selected depending on the size of the object and the amount of room you have on the paper to illustrate the drawing.

Dimensions

Engineers use drawings to show the shape of their design and different types of lines to show features of their drawings, but they must also share the size of the drawing. ***Dimensioning*** is a process used to describe the size of the object as well as the location of different features of the design. When dimensioning, engineers use two different types of lines: extension lines and dimension lines. Extension lines are drawn from very near the edge of the object to outside the view. Extension lines can also be drawn from a feature in a drawing. Dimension lines are drawn between extension lines and have arrows at the end of each line. The middle of the dimension line is where an engineer provides the actual measurement, or dimension text, for the object. **Figure 5-17**.

There are three types of dimensions in a drawing. First, engineers use ***size dimensions*** to describe the length, width, and depth of an object. Next, engineers may use a ***location dimension*** to show the distance between two different features. Location dimensions can be used to show the distance between two endpoints, the center of two circles, or any other feature in the drawing. Lastly, ***shape dimensions*** are used to provide detailed information about the shape of features. Usually, shape dimensions are used to show angles between different features of the object.

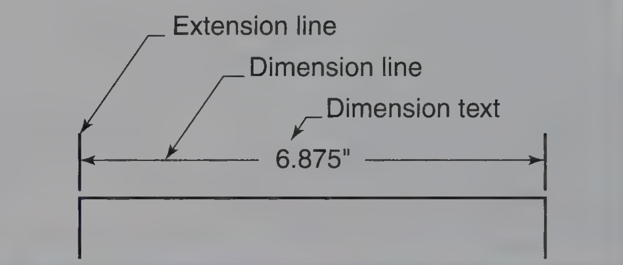

Figure 5-17.

This example shows the extension lines, dimension lines, and dimension text.

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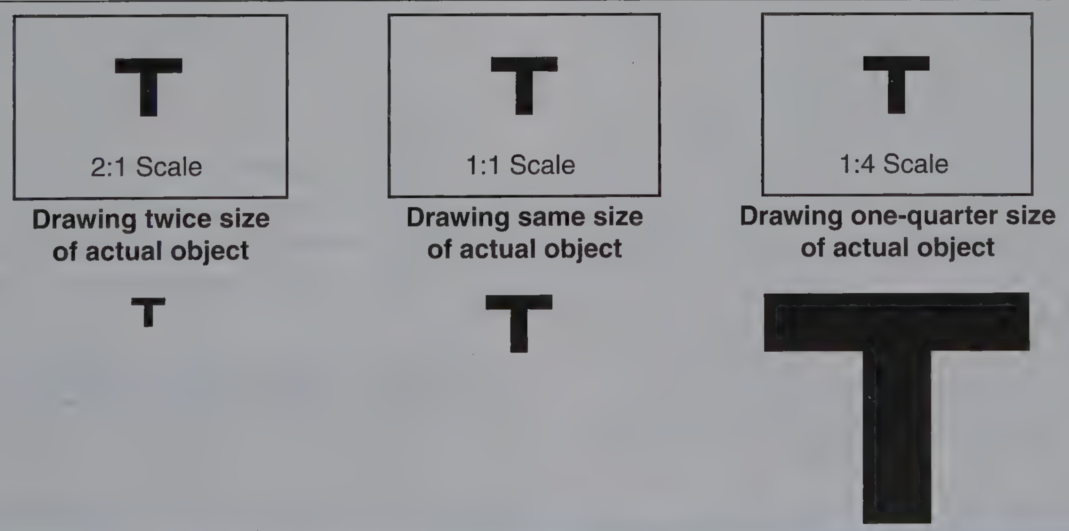

Figure 5-16.

Different scales are used to enlarge or reduce a drawing.

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Much like the standard use of symbols in drawings, there are certain rules engineers follow when they provide dimensions. These include the following rules:

- Dimensions should not be placed inside an object.
- Preferable, dimensions should be placed between views, rather than along the outside of an object.
- Dimensions should be placed on the view best showing the measurement. Engineers must decide which view best describes the object.
- The location and size of all circles and arcs must be shown.
- All circles and arcs must be dimensioned in a drawing.

To show the size of a circle or arc, engineers use a leader. A ***leader*** is a line with an arrow on the end pointing to the feature. Circles are identified by using diameter for a size dimension, and arcs and other incomplete circles use radius as a size dimension. See **Figure 5-18**.

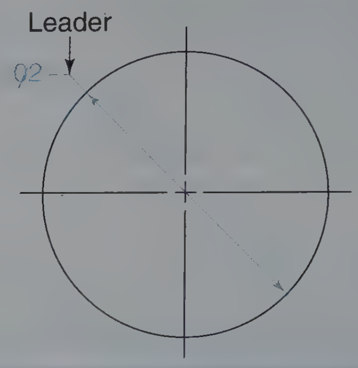

Figure 5-18.

This example shows the leader line, which points to both the object as well as information about the object.

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Industry Guidelines

Engineering drawings follow the standard guidelines provided in this chapter, but it is important to note that there are discipline-specific drawing guidelines. Biological engineers use different types of drawings from mechanical engineers, although many of the basic principles stay the same. Companies and organizations may also have their own procedures and guidelines for drawings.

The guidelines provide the specific procedures, methods, and organization of the engineering design process used by a company's engineers.

Company guidelines typically cover the following criteria:

- **Drawing elements.** There are specific guidelines for the size and format of each drawing. Included in the criteria is the proper size of paper and location of title information for the drawing.
- **Nomenclature.** Nomenclature is the proper ways to label objects in the drawings. Included in this label are specific abbreviations to use, the proper ways to title different objects, and the requirements for listing materials for each component.
- **Drafting practices.** Drafting practices are general guidelines. Companies develop specific guidelines for different use of line types, lettering, and the use of scale. Also included are specific guidelines for where the object is located on the page of paper.
- **Types of drawings.** The guidelines provide a list of appropriate drawings created by engineers. Listed are detail drawings, assembly drawings, schematic drawings, and many other content-specific drawing types.
- **Drawing revisions.** Also included are detailed descriptions of how to make revisions to drawings. As discussed in this text, engineers often make changes to drawings, and organizations outline specific procedures used to make sure changes are documented during the process.
- **Design references, standards, and specifications.** Guidelines outline the dimensioning processes, types of units used, and the types of standards, specifications, and symbols used for all company or organization design drawings.

At the end of the manual are guidelines for engineering design drawings. Most guidelines include information about accurate dimensioning and methods of reporting information such as size, materials, and part locations.

The attention to detail when reporting information accurately is critical to ensure designs are properly modeled, tested, and created.

Summary

- The communication of solutions is important to make the design clear to everyone.
- Working drawings are the most complete drawings produced. These types of drawings are detailed drawings, assembly drawings, and schematic drawings.
- Two types of drawings classifications are orthographic and pictorial. Orthographic drawings can be one-view, two-view, or three-view drawings. Pictorial drawings include isometric, oblique, and perspective drawings.
- Standard symbols are used throughout various engineering disciplines to represent different entities in a drawing.
- The five primary line types are construction lines, object lines, hidden lines, centerlines, and border lines.
- Dimensioning is a process used to describe the size of the object as well as the location of different features of the design.
- The two line types commonly used in dimensioning are dimension lines and extension lines.
- Industry guidelines allow for use of standard guidelines as well as industry- or organization-specific guidelines.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. Why is communicating solutions important?
2. Explain the difference between a detailed drawing and an assembly drawing.
3. How is a schematic drawing used?
4. What is *visualization*?
5. Explain when you would use the following drawings:
   A. One-view drawings.
   B. Two-view drawings.
   C. Three-view drawings.
6. A(n) _____ drawing is used to communicate a design to someone who does not understand isometric drawings.
7. Which type of drawing do engineers use to highlight one feature of an object?
   A. Isometric.
   B. Oblique.
   C. Perspective.
   D. Orthographic.
8. What does a perspective drawing show?
9. Symbols are regularly used in _____ drawings to represent different parts of an electric or hydraulic circuit.
10. What are the two major organizations that develop symbols for use throughout different engineering disciplines?
11. Describe why the following line types are used:
    A. Construction lines.
    B. Object lines.
    C. Hidden lines.
    D. Centerlines.
    E. Border lines.
12. Explain the difference between dimension lines and extension lines.
13. List three different types of dimensions.
14. What is a leader?
15. *True or False?* Engineers within different disciplines use the same types of drawings.

Reinforce learning

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

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Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 6

Modeling, Testing, and Final Outputs

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- Explain the importance of predictive analysis to the engineering design process.
- Describe principles used in mathematical modeling.
- Identify different types of physical modeling.
- Discuss how computer modeling is used in different engineering fields.
- Explain the testing process.
- Describe different types of final outputs.

Key Terms

aesthetics
assumption
computational fluid dynamics (CFD)
computer modeling
engineering economics
environmental impact
final project report
formula
function
geospatial modeling software
mathematical model
mock-up
oral presentation
predictive analysis
reverse engineering

Practice *vocabulary*

Engineering designs must be functional and solve the problem they intend to solve. In the planning stages, as you have read about in previous chapters, engineers brainstorm different ideas, research solutions, and develop drawings to help communicate their designs. It is during these planning stages that all ideas are considered and refined. Once the ideas are refined, engineers develop models to test their solutions. Many of the modeling and testing procedures in this chapter are mixed into the design process at varying times, but one thing is for sure, engineers must test and model any solution before it is created and used by individuals.

Many engineers do not have the opportunity to create a full-size model of their solution, so they rely on the different techniques discussed in this chapter to simulate their design in daily use. For example, structural engineers cannot build full-size sample bridges to check the strength of the trusses, but they can create a small scale model or use a computer simulation to observe the structure when weight is applied.

In this chapter, you will learn about the stages of the testing/analysis step of the engineering design process. This includes different modeling methods as well as how these models are tested. Also discussed in this chapter are the final outputs produced by engineers. See **Figure 6-1**.

Modeling

Engineers use modeling in many different ways. The specific field for each engineer determines the types of models used, but all models are classified in at least one of the four areas of modeling: mathematical, physical, and computer.

Mathematical Modeling

Mathematical models are used to find solutions to problems using mathematical prediction. Mathematical prediction uses mathematical formulas and problems to predict the results of a design. Engineers rely on mathematics to find their solutions to problems. Using mathematical principles, engineers predict how certain materials will respond to stress, how chemicals will work together, and how electricity will travel through a circuit. The use of mathematical models is highly dependent on the type of engineer working on the problem. See **Figure 6-2**.

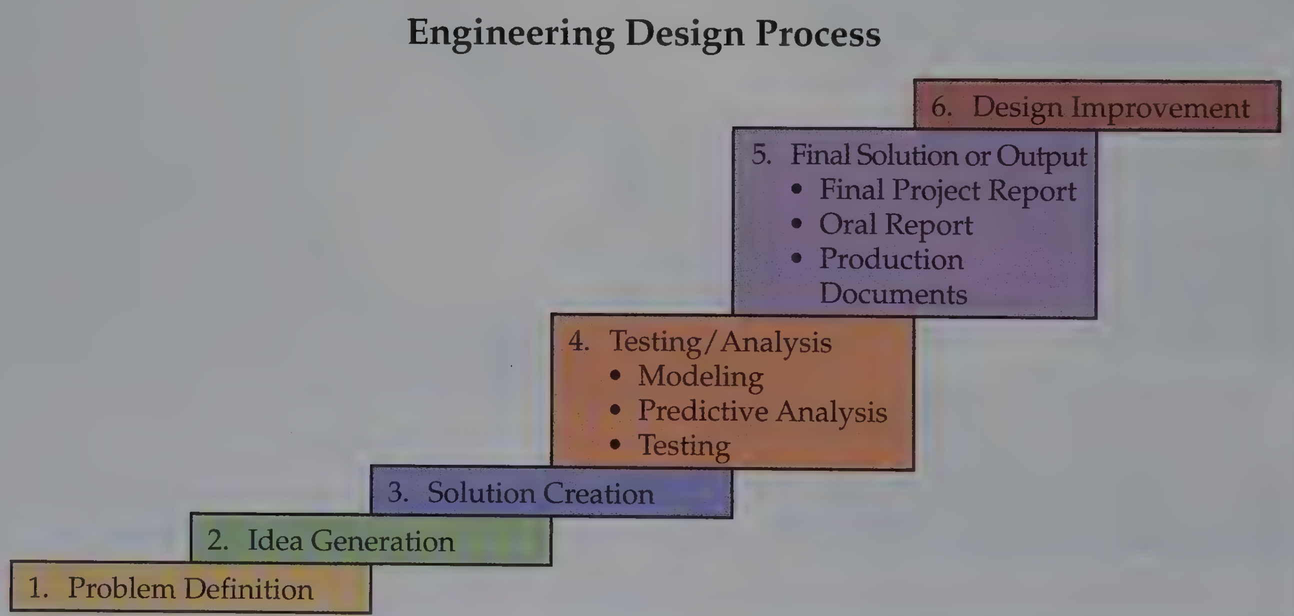

Figure 6-1.

The testing/analysis step of the engineering design process includes modeling and testing. The final solution or output step includes various ways of reporting the final solution.

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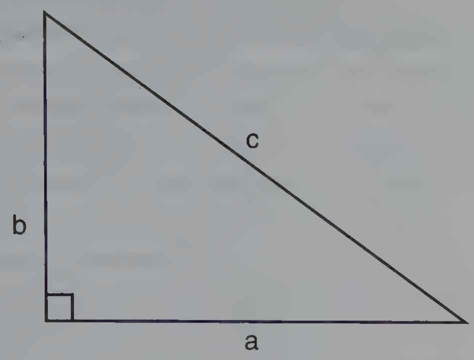

$$c^2 = a^2 + b^2$$
$$c = \sqrt{a + b}$$

Figure 6-2.

The types of mathematical models used typically depends on the engineering discipline. Some basic formulas will be used by engineers in all fields, but more complex formulas are specific to a particular field.

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Units of Measurement

When using mathematical modeling in engineering, it is important to have an understanding of measurement and the types of units used in engineering disciplines. Each discipline has specific units of measurement used to determine size, strength, pressure, or other material properties. Some common measurement units used by engineers include:

- **Angle.** Normally measured in degrees.
- **Length.** Measured in metric (millimeters, centimeters, meters) and US customary (inches, feet, yards).
- **Area.** Measured in metric (square millimeters, square centimeters, square meters) and US customary (square inches, square feet, square yards).
- **Volume.** Measured in metric (cubic millimeters, cubic centimeters, cubic meters) and US customary (cubic inches, cubic feet, cubic yards).
- **Mass.** Measured in ounces, pounds, grams, kilograms.
- **Force.** Measured in pound force, kilogram force, newtons, ton force.
- **Torque.** Measured in pound-feet, newton-meters.
- **Pressure.** Measured in Pascals, pounds per square inch, pounds per square foot.
- **Energy.** Measured in Joules, foot-pound.
- **Power.** Measured in horsepower, watts.

Fields of Mathematics

While all areas of engineering rely on mathematical modeling, specific types of models are relied on by engineers in their respective fields. More specifically, many different fields of mathematics are used by engineers. The most common fields of mathematics used by engineers include:

- **Algebra.** A branch of mathematics that is concerned with operations and the relationships between numbers. Letters are used to represent different numbers and equations are used to find missing information, based on established relationships.
- **Geometry.** The branch of mathematics focused on the size, shape, and distances between different objects.
- **Trigonometry.** A branch of mathematics focused on the relationships between sides and angles of triangles.
- **Calculus.** A branch of mathematics focused on limits, functions, derivatives, integrals, and infinite series.
- **Statistics.** The branch of mathematics focused on the collection, analysis, explanation and presentation of data. Statisticians use research studies and experiments to gather and explore information.
- **Probability.** Probability is often linked to other mathematical fields, such as statistics and algebra. Probability is the ability to take data and predicate what will happen under specific circumstances.

Formulas

Mathematical models rely on formulas to represent a concept and predict the outcome of a potential solution. A ***formula*** is a series of mathematical symbols that represent a rule or relationship between concepts. Numbers and letters are used in formulas. Numbers are part of the calculation of a formula and letters are used as symbols that represent the concepts that engineers are trying to identify.

For example, the formula to determine the amount of work performed by a machine is $w = f \times d$. In this formula, w is the amount of work produced, f is the amount of force applied to the object, and d is the distance the object moved. So if we have a machine that applies a 20-lb force to move an object a distance of 5′, the machine produces 100 ft-lb of work.

The formula for work is simple in comparison to the more complex formulas engineers use to model most engineering problems. Mechanical engineers use many formulas to gain information about their designs such as determining the amount of power in a system. The formula for power is $p = w/t$. In this formula, p is power, w is work, and t is time. This formula shows the amount of kinetic energy produced during a process.

Another type of formula used by engineers is the mathematical model of Ohm's law. Ohm's law, discussed in Chapter 7, defines the relationship of resistance, voltage, and current in an electrical circuit. According to Ohm's law, the formula used to calculate the voltage in a circuit is $E = I \times R$. E represents the value for voltage, I represents current, and R stands for resistance. In a simple circuit that has a current of 2 A and a resistance of 5 Ω, using the formula, we see that this simple circuit has a voltage of 10 V.

Many complex formulas are used by engineers in many different fields. For example, mechanical engineers use the Bernoulli's principle to study fluid dynamics. The following is Bernoulli's principle for incompressible liquid flows:

$$\text{constant} = V^2 + gz + p / 2\,\rho$$

Math

Pythagorean Theorem

The Pythagorean theorem is used to find the length of one side of a right triangle when the values for the other two sides are given. A right triangle has one 90° angle. You can use the Pythagorean theorem to find the length of the side opposite the 90° angle, or the hypotenuse. The theorem states that the square of the hypotenuse is equal to the sum of the squares of the other two sides of the triangle.

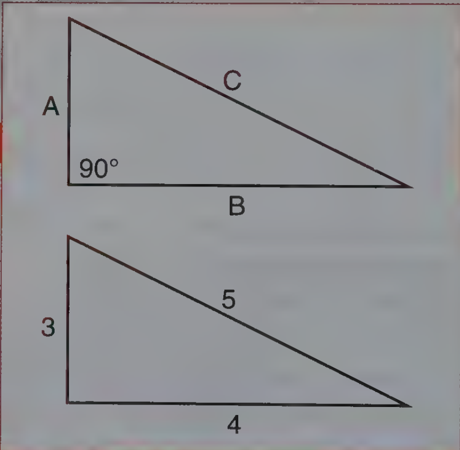

Figure A.

Goodheart-Willcox Publisher

The mathematical formula for this theorem is:

$a^2 + b^2 = c^2$

For example, if side a was equal to 3, and side b was equal to 4, we could find the length of the hypotenuse using the formula. See **Figure A**.

$3^2 + 4^2 = c^2$

$9 + 16 = 25$

$\sqrt{25} = 5$

Side $c = 5$

Find the hypotenuse for each of the following triangles.

1. $a = 4, b = 6$
2. $a = 12, b = 4$
3. $a = 7, b = 5$
4. $a = 9, b = 15$
5. $a = 2, b = 3$
6. $a = 5, b = 13$

Understanding the symbols is critical for mathematical modeling. In Bernoulli's principle, the v stands for the fluid speed, g is the acceleration of fluid due to gravity, z is the elevation point, p is the pressure and ρ is the density of the fluid.

Common mathematical formulas used by engineers from different disciplines are included in later chapters of this text.

Physical Modeling

Physical models are 3-D replicas of the final design of a solution. Models are used to illustrate the design, test the design, or experiment with materials. Physical models usually fall into two categories: mock-ups and prototypes.

A ***mock-up*** is a physical model that is used to show the design of an object. Mock-ups are built at full size or scaled to decrease or increase the size of the object to make it easier to view. Mock-ups are primarily used to demonstrate the object to others, to illustrate particular features of an object, or to evaluate the design. Designs progress from a paper drawing to a mock-up because engineers want to learn about how the product will look when it is created. Mock-ups are also used to obtain feedback from other people involved in the design project. Mock-ups are usually created with less expensive material than the final design. Mock-ups may use any material, but mock-ups are normally created with paper, cardboard, or foamboard to simulate the appearance of the final product. See **Figure 6-3**.

Tools

3-D Printers

One tool used to create models of objects is 3-D printers. 3-D printers use plastic placed in layers to create a model of an object. A 3-D printer "prints" by creating these layers.

Engineers design an object in a CAD software program. When they print their design, they send the file to a 3-D printer. The 3-D printer heats plastic and layers the plastic to create the object.

Technology has changed dramatically in the 3-D printing industry over the last 20 years. Machines have reduced and price and can now be used by consumers at home.

Figure 6-3.
Mock-ups show what a final design will look like, though the materials used in a mock-up are only intended to simulate the appearance.

FikMik/Shutterstock.com

Depending on the specific engineering discipline, mock-ups vary in size and shape. For example, when designing an automobile, engineers create a model car out of plastic material with paint and detailed features. Chemical engineers create mock-ups to allow engineers to handle simulated radioactive material instead of dangerous chemicals. A biological engineer creates a mock-up of a farm field to help illustrate how a new pesticide works in a farmer's environment. Electrical engineers create mock-ups of electrical circuits to show how different electrical components will fit into a new household appliance. While they come in many shapes and forms, mock-ups are important to communicate a design by providing the overall appearance of the design.

A prototype is different from a mock-up because it is a working product. Prototypes are physical models that simulate the function of the final object. Engineers often begin by developing a mock-up to receive feedback on the overall look of a project. Once they gain approval from customers or members of the design team, engineers create a working prototype. Prototypes come in many shapes and forms. Some are complex, detailed, and intricate, while others may be rough prototypes to test the effectiveness of the solution. See **Figure 6-4**.

Rapid prototyping is a method in which engineers use a computer modeling program to develop a prototype. Rapid prototypes are made on a machine that takes information from a CAD program and builds the product by making horizontal passes and building layers of plastic.

Computer Modeling

Over the last 30 years, computer modeling has replaced many of the traditional methods of creating models. ***Computer modeling*** is using computer software to create useful models for engineers. See **Figure 6-5**.The use of computer modeling has created new ways of modeling objects, but it has also made the previous methods modeling discussed easier to complete and utilize. For example, engineers now use computers to prepare mock-ups of their ideas using computer numerical control (CNC) devices. Also, computers allow engineers to create graphic models using software. This previously required an engineer to draw advanced models by hand.

Computer modeling software is used to create simulations of different situations. These models are a form of predictive analysis. Engineers use simulation software to virtually test their designs and make any necessary adjustments

Figure 6-4.

This prototype machine is being used to create a clay mock-up of a vehicle.

Ronen/Shutterstock.com

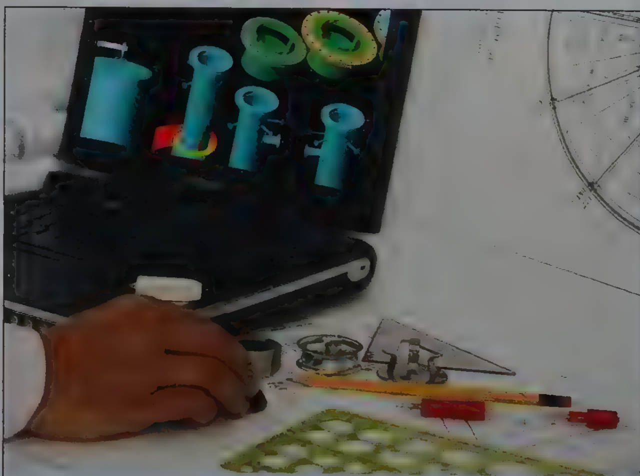

Figure 6-5.

Rather than drawing these nozzle flanges by hand using 2-D drawing methods, this engineer has produced 3-D models of them using computer modeling.

RAGMA IMAGES/Shutterstock.com

before production. For example, engineers use computer modeling to virtually test the amount of weight held by a bridge, the amount of friction produced in mechanical system, and the amount of energy lost in an electrical circuit. Using simulation software allows more accurate prediction and the ability to change different components of a system, including materials, arrangements, sequences, and combinations. Most engineers use specific programs developed for professionals in their discipline. See **Figure 6-6**.

Figure 6-6.

Engineers often use discipline-specific software to help them run simulations in order to test designs.

RAGMA IMAGES/Shutterstock.com

Chemical engineers use process simulators to create computer models of chemical properties. Process simulators use diagrams to show the flow of different chemical processes. More specifically, the process simulators show the mass and energy balances of different chemicals involved in processes.

Mechanical engineers use many different computer-controlled devices and software packages. Most frequently, mechanical engineers use 3-D modeling software to create functional computer models. 3-D modeling software allows engineers to take basic shapes and modify the size, shape, and other features to create visual working models. Once engineers design products in 3-D modeling software, they can send their designs to CNC devices or rapid prototyping to have their objects produced. CNC devices include specialized equipment, such as mills and lathes. Even once products are being produced by CNC devices, engineers can make adjustments through the 3-D modeling software to tailor their design for specific situations. See **Figure 6-7**.

Figure 6-7.

This engineer can continue to make changes to his design while the product is being produced by the CNC machine.

Dmitry Kalinovsky/Shutterstock.com

Biological engineers use different computer modeling tools because of their varied focuses in biology, medical, and agricultural uses. A few examples include environmental simulation software to determine the changing dynamics and physical properties of earth. See **Figure 6-8**. Environmental simulators take mathematical and scientific principles about earth and apply them to how species are currently living on earth. The computer models produced in these software packages show the impact of rising sea levels on earth or the impact of losing one species on our food chain. Biological engineers focused in the medical field use computer modeling to see the impact of different drugs on patients and to predict the effects of different medications for a group of people.

Structural engineers use specific software programs to help them draw and develop plans for structures. 3-D architectural design packages are available to allow structural engineers to test their designs as they create their structures. Historically, structural engineers have been able to use computer-aided design (CAD) software to draw two-dimensional drawings, but advancements by CAD technology has allowed structural designs to be easily created and manipulated in 3-D. Material properties are important in developing structures, and software packages allow for experimentation with different materials. Structural properties in examples on the computer. See **Figure 6-9**.

The field of electrical engineering has changed dramatically with the increased development of and access to computers. Many of the challenges electrical engineers encounter are computer based. Power system design and analysis software allows electrical engineers to develop circuits and calculate voltage flow and electrical load in computer animated models. Electrical engineers create models showing the relationship between time and current to find peak times of electrical use. See **Figure 6-10**.

Civil engineers encounter many challenges when planning the layout and organization of spaces used by people. To help address these challenges, geospatial modeling software allows engineers to simulate and better organize urban areas.

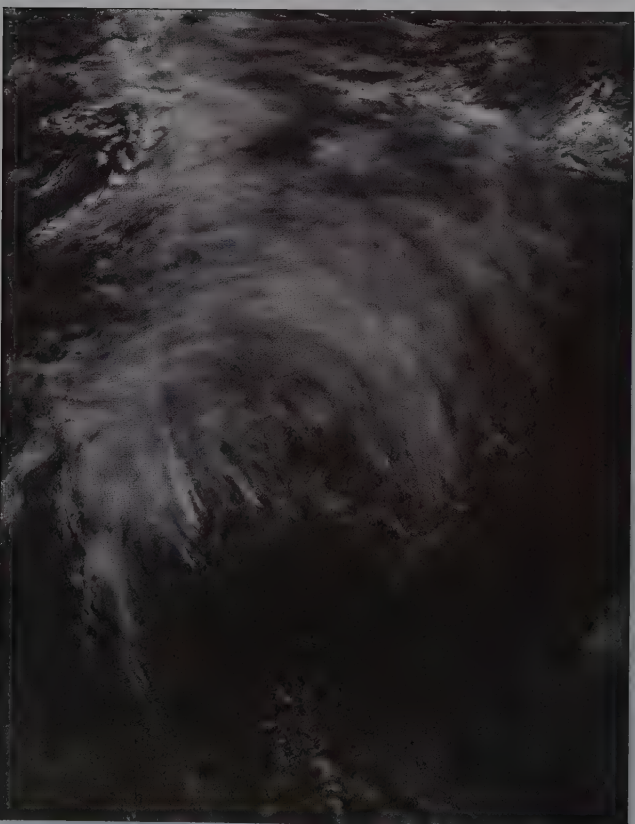

Figure 6-8.

Environmental simulation software can show how wildfires look from space.

NASA

Figure 6-9.

This structural engineer can use modeling software on his tablet to test his design.

Peter Bernik/Shutterstock.com

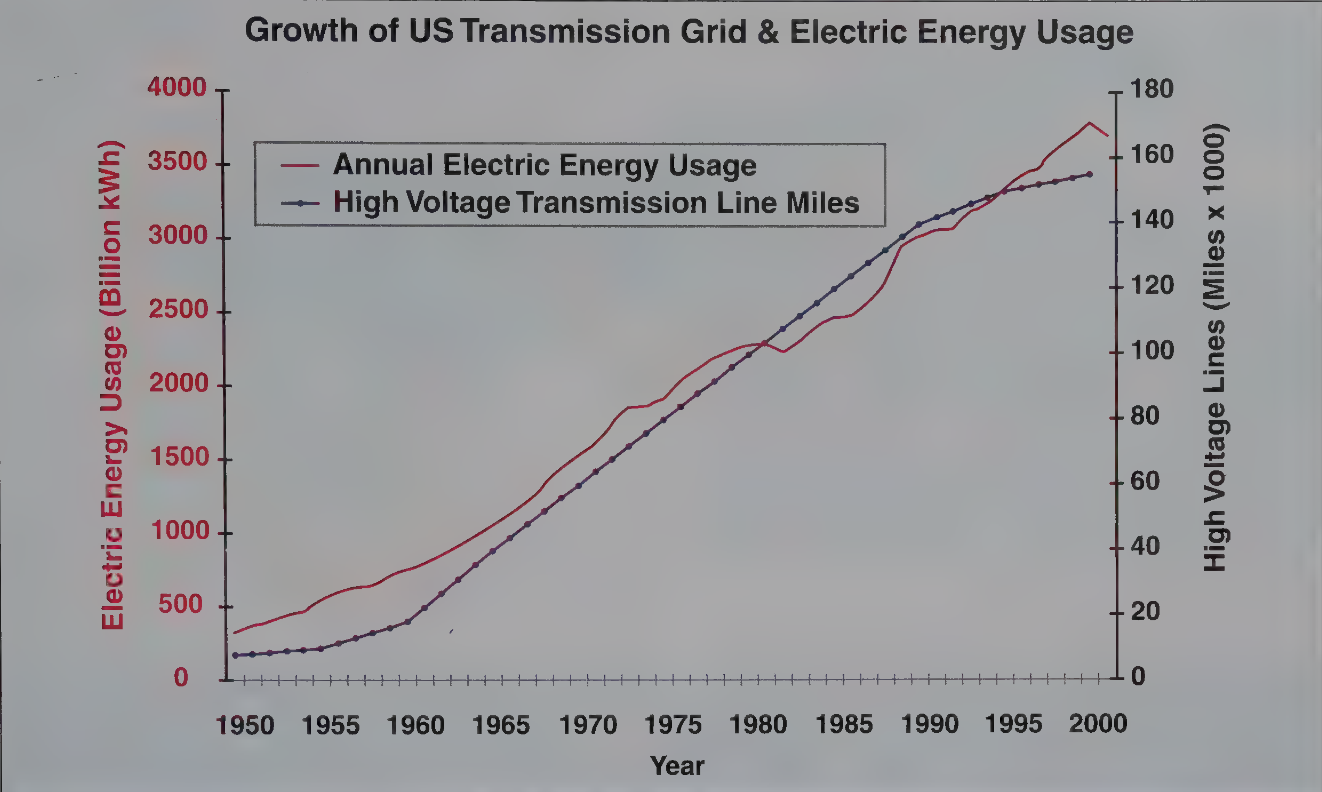

Figure 6-10.

Analysis software helps engineers develop more efficient designs based on collected data, such as in time vs. current models.

NASA

Geospatial modeling software uses spatial and analytical methods integrated with information about the earth's surface and data about people to create models. This software allows engineers to plan and adapt areas while taking many different factors into consideration. See **Figure 6-11**.

Aerospace engineers use prototypes, models, and wind tunnels to determine how to develop vehicles for flight. Now, aerospace engineers also use ***computational fluid dynamics (CFD)*** software. CFD software focuses on the use of fluids (air) in relationship to the flight of airplanes. CFD software helps aerospace engineers study the way airplanes gain lift in the air and the forces that work against flight. CFD uses many different mathematical algorithms and fluid properties to create solutions to design problems. Once aerospace engineers develop approximate solutions using CFD, they test their designs by using wind tunnels and flight tests. See **Figure 6-12**.

Figure 6-11.

Civil engineers use computer modeling software to better plan their designs.

Norman Pogson/Shutterstock.com

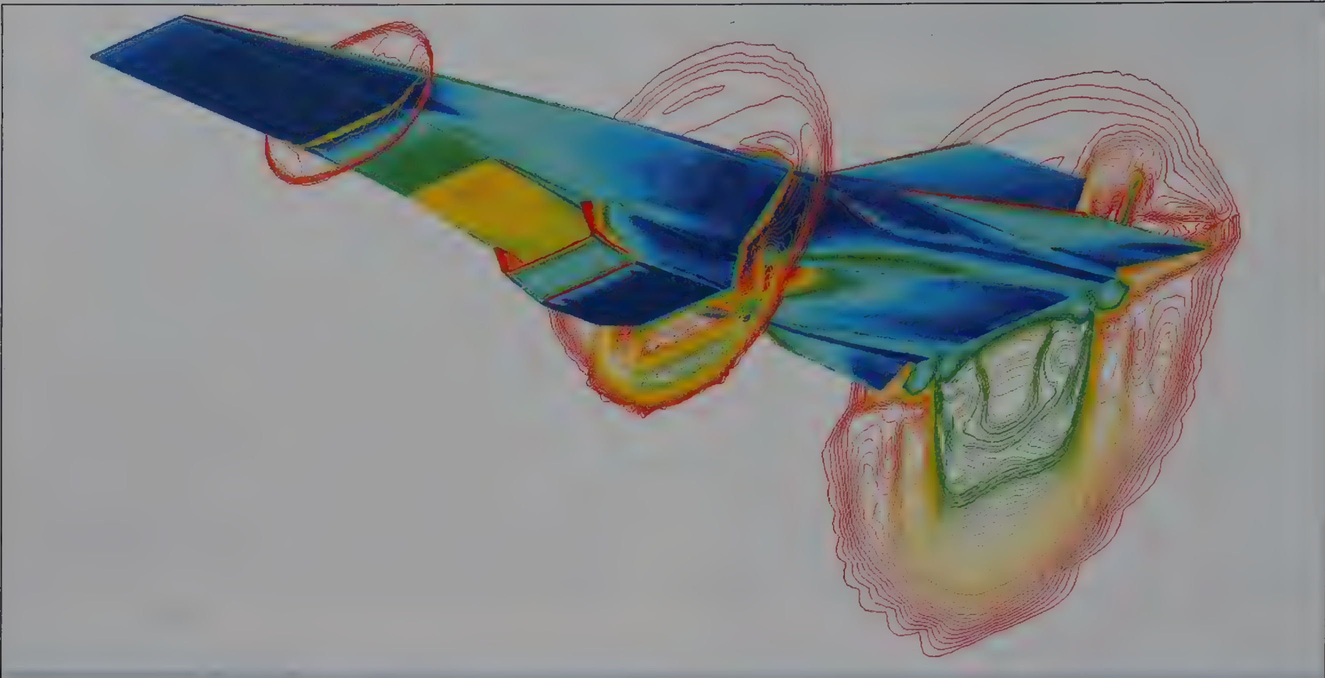

Figure 6-12.

CFD software helps aerospace engineers study their designs before testing.

NASA

Predictive Analysis

The most important tool used by engineers is predictive analysis. ***Predictive analysis*** uses many different factors, including statistics and theoretical models, to predict future events. Predictive analysis distinguishes engineering design from other types of design including technological design and trial and error methods.

Engineers must determine if their solution will solve the problem without building the actual object. Using predictive analysis methods, engineers have mathematical and scientific principles to support their conclusions. Predictive analysis is based on statistics and probability of certain occurrences.

Assumptions are ideas that are believed to be true and used in engineering design. Assumptions are used to simplify mathematical models, but can reduce the overall effectiveness of the predictive analysis.

Engineers use predictive analysis to determine if certain materials will hold the proper amount of weight or if two chemicals will work together properly to create a new compound. Predictive analysis is performed using methods of modeling. With the increase in engineering software programs, most models are created using computer software, but engineers still rely on mathematical, physical, and graphical predictions. See **Figure 6-13**.

Figure 6-13.

Different types of software have allowed for help with predictive analysis.

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Testing

Engineered products must be tested to determine the usefulness of the product. Testing procedures may be completed at different times during the development of the design, but testing is always completed before the design is produced. Testing begins by engineers asking questions about the design. Tests must be done in order to answer some of these questions. Computer modeling software can complete some testing, but prototypes are also tested for effectiveness.

Engineers test their products based on five criteria: function, fit, aesthetics, safety, and environmental impact. All five criteria must be addressed before a design is finalized to be used by people.

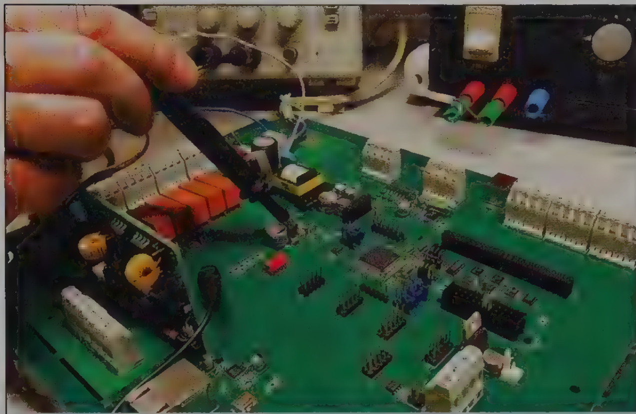

Figure 6-14.

Electrical engineers can test their designs to ensure everything functions as expected.

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Function

Function is usually the first criteria tested. When engineers perform tests to determine the ***function*** of a product, they are determining if the product works properly. Engineers ask themselves a series of questions to ensure the design is functional. See **Figure 6-14**.

The first question addressed to determine function is whether the product works. Engineers test the prototype to make sure it solves the problem they intended to address. When they look for functionality, they must look beyond the overall question and further question the design by looking into scenarios the device may encounter.

Science

Scientific Observations and Experiments

In the engineering design process, tests are done to check the quality and function of a design. In the scientific method, the goal is to test a hypothesis. There are two ways to test a hypothesis: observations and experiments.

Sometimes it is difficult or impossible for scientists to perform experiments or run tests. However, data must still be gathered in order to come to a conclusion. In these cases, observations can be made. For example, before we were able to send people or objects into space, we were able to test hypotheses by observing space from a distance. The observation method allows scientists to watch without interfering or introducing variables in order to test their hypotheses. Sometimes, observation is used because scientists want to collect data on the natural state of something before introducing any variables. For example, for scientists wanting to learn more about wild animals in their natural habitat, they may observe the animals and record data.

Experiments are also used to test hypotheses and collect data. Through experimentation, scientists are able to verify or disprove a hypothesis. Experiments are tests typically run with controlled elements and one variable. Having only one variable allows scientists to more accurately determine what causes a change in a controlled environment. All the factors remain the same except for one, which is an independent variable.

The data collected during observation and experimentation can be used to help scientists determine whether their hypotheses were true or false. If necessary, scientists can continue observing or change the independent variable in an experiment to help them reach conclusions about their hypotheses.

Sample questions include:
- Will the product work in cold and hot temperatures?
- Will the design withstand daily use?
- Does the product work as suggested by the mathematical modeling?
- Does the product work smoothly?
- Does the product complete its task at the correct speed?
- Is the part soft/hard enough?
- Does the product meet minimum requirements?
- Does this design work to customer expectations?

Engineers use many different types of tests and information to answer the provided questions. Most commonly, they perform repeated tests on the prototype in different conditions to determine its ability to complete the desired tasks. Also, engineers will revisit their research data to make sure their findings are consistent with the research they conducted. See **Figure 6-15**.

Fit

Another step in the testing process is to look at the fit. The fit of an object involves its ability to fit into the production process and its use by the customer. The overall question to determine the fit of product is whether the product works with production and customer needs. More detailed questions include:
- Can this design be produced efficiently?
- How does this product fit into our manufacturing facility?
- Do different parts of the design interfere with other parts?
- Does this design fit in the consumer's hand?
- Is this product comfortable to use?
- Are there ways we can make this product more useable?

Questions about the fit of the project are answered through two primary methods. One method is discussion and testing with the design and production teams. The other is allowing potential users to try the product.

Discussions between designers and production staff are critical to determine the fit of the product. Manufacturers often see challenges in production that the engineer did not anticipate or that did not appear in the modeling software or mathematical models. An example of a problem in production could be an inability to place a feature in a specific spot on the device because of manufacturing limitations. More specifically, the design for a product, such as a new phone,

Figure 6-15.
Engineers test prototypes to check results against their initial research data.

Dmitry Kalinovsky/Shutterstock.com

may have a power switch on the bottom of a unit. The manufacturing facility may not be able to place the switch in that specific location because of the processes used.

Consumers who will use a product may also find problems with the design. For example, a product may not fit comfortably in a person's hand. A product may be too loud for consumers to use. A car may be uncomfortable for a person to drive. Consumers can provide valuable feedback to engineers. Often, consumers provide feedback about how a product or design does *not* work for them.

Aesthetics

Aesthetics is another criteria. ***Aesthetics*** is whether or not the product is visually appealing to potential customers. Engineers must ask if the product they developed is appealing enough for people to use. See **Figure 6-16**. Sample questions asked about the product include:

- Is this product visually appealing?
- Will consumers purchase this product based on its appearance?
- Is the product the correct size and color?
- What could make this product more appealing?
- Does this product look like it can solve the problem?
- Is the design too plain or too radical in appearance?

To find answers to these questions, engineers ask themselves, but they also ask potential customers. Designers may ask for product testers to see the product and provide feedback. They also create multiple prototypes with different style features to determine which designs are most popular with potential consumers.

Safety

Safety is always a major consideration for engineers. During testing, engineers ask themselves if the product is safe. Engineers are concerned with two forms of safety. First, they look to determine if the product is safe to produce. Second, they try to determine if the product is safe for consumers. Many of these questions were addressed with mathematical modeling and computer modeling, but engineers want to further ensure safety by testing prototypes.

Figure 6-16.

This concept art for a bicycle is being tested for its aesthetic value.

fet/Shutterstock.com

See **Figure 6-17**. Safety questions to consider include:

- Will the material be safe to manufacture?
- Is the material strong enough to support proper function?
- Will this product be dangerous to produce because of its design?
- Will parts of this design be unsafe when wet?
- Are there any electrical hazards with this device?
- Will any pieces break during usage?
- Will any pieces pose a choking hazard for young children?
- Does this product meet all government safety regulations?

To find answers to these questions, engineers use a variety of testing procedures. First, much like function testing, they put the product through repeated testing procedures to determine durability and safety. Engineers investigate the materials to make sure they are safe to use in the product. Also, engineers check to make sure the product meets all the appropriate safety regulations.

Environmental Impact

Engineers are becoming increasingly focused on the ***environmental impact*** of their designs. The overall question engineers ask is whether the design is safe for the environment. Engineers must ensure their product will have minimal impact on the environment. Consumers are interested in environmentally responsible designs. Therefore, it is important for engineers to ensure their designs are safe for the environment. See **Figure 6-18**.

Figure 6-18.

Testing a design for its environmental impact can help determine the types of waste materials associated with the product.

ssuaphotos/Shutterstock.com

Figure 6-17.

A crash test can test safety in a vehicle. Testing for safety can be done with mathematical modeling and computer modeling first, but testing the prototype is another way to ensure the design is safe.

Stefan Ataman/Shutterstock.com

Some questions engineers may ask themselves include the following:

- What environmental impact will occur during the production of this product?
- Are there waste materials associated with the manufacturing of this product?
- What types of waste materials are produced when using this product?
- How will this product be disposed of when it is no longer useful?
- What is this product's ecological footprint?
- Are there potential risks if this product malfunctions?

To find answers to the above questions, engineers perform tests on the manufacture of the product and talk to manufacturers about the materials used in production. Also, engineers refer to their research conducted during earlier stages of the design process to ensure they have implemented their designs properly. Also, design teams check with government environmental regulations to make sure they are following the appropriate guidelines.

Engineering Economics

Engineering economics is an important part of creating and distributing engineering design solutions. ***Engineering economics*** is all of the financial considerations and decisions made during the production of a new design. Some engineering firms have economists that are responsible for the overall financial picture of a product, but the engineer is critical in determining the cost to develop and produce design. See **Figure 6-19**.

Engineers look at a few different criteria when determining the cost feasibility of the product. As discussed in Chapter 4, cost feasibility is considered through the entire design process. At the end of the process, the engineer must make decisions about whether or not the product is worth producing and if there are opportunities for the company to make a profit. Market researchers help in this decision. Often, once a product is ready to be produced, engineers adjust certain materials to make the product more desirable or less expensive to create.

Figure 6-19.

Many factors go into determining the overall cost for a product. However, engineers must be involved in determining the cost to develop and produce the design.

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Final Outputs

The final output for an engineer is the final step in a long and rewarding process. There are three types of final outputs for an engineering design: final project report, oral presentation, and production documents. First, engineers share the final outputs with a management team, and then they present their information to a client, community, or other group of interested people. The management team is a group of people overseeing the entire project. Often, the management team will include engineers, high-level production staff, and business specialists. This team reviews the overall design to ensure the product or solution is fundamentally appropriate, is able to be produced, and follows the appropriate business model.

Final Project Report

The ***final project report*** summarizes the design process for management and potential customers. Final project reports are highly personalized for each specific project, but the overall goal is to provide information about why the engineering solution developed is the best option to address the original problem. Final project reports provide a brief summary of each step of the process.

Going Green

Green Structures

Figure A.

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Engineers are increasingly focused on the environmental impact of their designs. The environmental component of designs is a consideration when determining the effectiveness of a solution. General environmental principles are included in all designs, such as the waste of production materials, the impact on the environment of producing products, and the ecological footprint of production and distribution of the product. While these considerations are critical, some organizations have developed measureable ways to provide guidance for more environmentally friendly designs. Instead of engineers determining how they can make a product more ecologically responsible, engineers are looking to organizations to provide specific specifications and certifications to ensure the responsible development of their design.

One organization providing leadership in environmentally responsible designs is the United States Green Building Council (USGBC). The USGBC is an organization focused on improving the environmental properties of building structures. To help accomplish their goal of a decrease of ecological footprint from structures and humans using the structures, the USGBC developed the Leadership in Energy and Environmental Design (LEED) certification process. LEED provides owners and operators a framework for identifying and implementing practical and measurable green building design, construction, operations, and maintenance solutions. The LEED process is applicable to all types of construction. See **Figure A**.

LEED certification is based on seven main criteria:

- **Sustainable sites.** Sustainable sites criteria is focused on designs that are sensitive to plants, wildlife, water, and air quality. This criteria suggests that the building should minimize the impact on land consumption, ecosystems, natural resources, and energy use while taking into consideration the existing neighborhoods, urban infrastructures, and existing transportation networks.
- **Water efficiency.** The water efficiency criteria is aimed at minimizing the amount of water used in a building. LEED certification requires a 20% reduction in water use in comparison to similar, non-LEED structures. Reductions are achieved by installing water-efficient fixtures, fittings, and appliances.
- **Energy and atmosphere.** The energy and atmosphere category is focused primarily on building energy performance, limiting chlorofluorocarbons (CFCs) and the use of renewable energy. CFCs are chemicals containing atoms of carbon, chlorine, and fluorine. CFCs are commonly used in aerosol sprays. The building should avoid air and water pollution and primarily focus on biomass, solar, and wind energy.
- **Materials and resources.** The materials and resources category requires strategies for construction, waste management, and material selection. This category suggests minimizing construction waste, the use of recycled materials, using regionally produced materials, reuse of materials, and the use of rapidly renewable resources.
- **Indoor environmental quality.** Indoor environmental quality relies on the use of automatic sensors and individual controls that can be integrated into the building system to control temperature, humidity, and ventilation.
- **Innovation in design.** The innovation category is used to provide points for new designs that may not fall into another category. The innovation credit provides incentive for engineers to look for new and innovative ways to provide environmental benefits through construction design.
- **Regional priority.** The regional credit is given to designs that meet a specific regional need in environmental construction design.

Based on the seven criteria described, the designs are given a score. This score is based on the level of achievement for each criteria. The scores range from 0 to 100. A LEED-certified building must have a score of at least 40 points.

More information including detailed criteria available on the website for the US Green Building Council.

The information typically provided in a final project report are further explained below.

The title page should include the title, lead engineers, and provide information about other members of the design team. The company information would also be listed along with the date and any other information that may help identify the project.

Engineers then list the problem statement they identified earlier in the process, as we discussed in Chapter 3. It may not be enough to just share the technical problem statement. Engineers may want to further describe the problem in nontechnical terminology for others to better understand.

Engineers summarize their design goals by discussing the different criteria and constraints they identified early in the design process. Engineers use the term *goal* to share their intent to model the perfect solution by addressing the constraints and criteria previously identified.

An alternative design is a solution the engineers decided not to use. Engineers present alternative designs in the final project report to show they explored different designs before choosing their final solution. Also, the final design may comprise different parts of the alternative designs. By sharing these designs, management and customers see how the engineer developed the final solution.

Engineers must be up front about the strengths and weakness of their products. In the final report, engineers share the trade-off matrix to explain why they chose particular materials, arrangements, or other features of their design. This also gives management and customers an opportunity to comment on the trade-offs the engineer chose and to offer suggestions.

Depending on the specific engineering project, the final report has information about the assembly and manufacturing of the product. This may be information for the customer, such as how to assemble the product, or it may be detailed information about how the product will be manufactured. Manufacturing information includes the processes and tooling used to create the design in the production facility.

Summary information on all of the testing is provided in the final project summary report. Information about the function, fit, aesthetics, safety, and environmental impact tests provide the management and customers assurance the product meets the required specifications.

The final recommended design is then discussed in the report. The design is shown through detailed drawings, mathematical models, computer-generated models, and prototypes.

A summary of what users of this product can expect is a summary of potential product performance. Engineers once again refer to their testing information to support the expected product performance. Also, engineers may share at this time the necessary maintenance and expected life of the product.

History of Reverse Engineering

Engineers use reverse engineering by taking apart an object or system to better understand it. After exploring the object, engineers often create 3-D models to gain a better understanding of the different components of the system and to make adjustments to the current system. Using computer modeling, engineers can change different features to explore possibilities.

Reverse engineering uses many of the same engineering skills described in this book, but usually has a different motivation than to solve a problem. Many times, engineers reverse engineer an object because they are missing documentation about the object or possibly by competing companies to learn more about another company's product. Reverse engineering is commonly conducted in software and computer environments as well as many other fields.

Historically, before computer modeling software was available for reverse engineering, engineers needed to physically take apart objects to understand the inner workings of the different systems involved in the design. Automobile companies would disassemble a car of a competitor to better understand the functionality of the design. Now, engineers can easily disassemble an object, make changes, and quickly reassemble a virtual model.

The final step in the report is to briefly summarize the solution and thank all members of the design team, management, production staff, and customers for their input and support of the project.

Oral Presentation

An ***oral presentation*** is the spoken delivery of a report to an audience. The audience for engineering design presentations is normally management teams or potential customers. An engineering design presentation will follow the final project report as an outline and allow the engineer to discuss the categories and show illustrations. See **Figure 6-20**.

Oral presentations follow various formats. Some design presentations allow the presenter only a few minutes to share their design, which forces the engineer to focus on summary information about their product. Other presentations may be over 30 minutes in length, which allows the engineer freedom to go into great detail of each category in the final report summary.

Presentation skills are important when presenting in front of a large group of people. Engineers must make sure their listeners are comfortable and can see any visuals and also hear the lead presenter. Also, it is a good idea to allow the audience members to ask questions about the presentation.

Production Documents

As a final output in the design process, engineers produce final drawings for many different stakeholders. Depending on the specific challenge, engineers produce final drawings that have all the appropriate dimensions and information to produce the product. Included in these final drawings is mathematical information, along with computer models that allow manufacturers to see how the product will be produced. These drawings, following the guidelines discussed in chapter five, will effectively communicate the engineers design solution with all members of the design team including management and production staff.

Design Improvement

The final step in the design process is design improvement. Engineers must take their designs and make improvements based on feedback from their design team, management team, production staff, and consumers. Reverse engineering is often used to create improvements in a design. ***Reverse engineering*** is a method of determining the properties or function of a device by taking it apart and looking at its operation structure. Reverse engineering uses many of the same principles used to create new products, but it begins with a current product engineers want to explore and learn more about.

Figure 6-20.
After the final project report has been written, engineers will often give oral presentations to show their designs to their teams and potential customers.

Yuri Arcurs/Shutterstock.com

Summary

- Predictive analysis helps engineers determine whether their designs will work prior to building the design.
- While all areas of engineering rely on mathematical modeling, specific types of models are relied on by engineers in their respective fields.
- Physical models are 3-D replicas of the final design of a solution. The two categories of physical models are mock-ups and prototypes.
- Computer modeling helps engineers create useful models using computer software rather than drawing intricate designs by hand.
- To test designs, engineers ask questions based on specific criteria. In order to answer the questions, tests must be performed.
- The three types of final outputs include final project reports, oral presentations, and production documents.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is predictive analysis?
2. *True or False?* Each engineering discipline has specific units of measurement used to determine size, strength, pressure, or other material properties.
3. List five common fields of mathematics used by engineers.
4. *True or False?* Mock-ups are developed to simulate the function of the final product.
5. How does rapid prototyping work?
6. Explain how computer modeling is a form of predictive analysis.
7. _____ software allows engineers to simulate and better organize urban areas.
8. What are the five different criteria engineers use to test their designs?
9. Engineering _____ is all of the financial considerations and decisions made during the production of a new design.
10. What is the purpose of a final project report?

Reinforce *learning*

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Chapter 7

Materials Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *materials engineering*.
- Identify different types of materials.
- Describe a range of material properties.
- List examples of material tests.
- Describe nanotechnology.

Key Terms

alloy
biomaterial
buckyball
ceramic
composite
compression strength
conductivity
corrosion
destructive material test
elasticity
flammability
manufacturability
materials engineering
melting point
metal
nanoparticle
nanotechnology
nanotubes
nanowire
nondestructive material test
plasticity
polymer
radiography test
resistivity
shear stress
strain
stress
tensile strength
thermal conductivity
thermal resistance
ultrasonic test

Practice vocabulary

New developments in technology are often the result of new or improved materials. In fact, human history is commonly divided into time periods based on the use of materials. The Stone Age, Bronze Age, and Iron Age are named after the materials that revolutionized those time periods. Although time periods are no longer named in that fashion, materials still have a large impact on technology and civilization. The Information Age, our current time period, relies on materials such as silicon, silica, and plastics. See **Figure 7-1**. These materials are used in computer processors, fiber optic communication, e-readers, LED televisions, and thousands of other modern products. These products have been developed as a result of new advances in the understanding of materials. Materials engineers often create new materials or find new ways to use existing materials.

Materials engineering is the understanding and modification of the structure and properties of materials to improve the performance and processing of the material. The understanding of science is an important aspect of materials engineering. In fact, it can be difficult to distinguish materials engineering from materials science. Materials engineers work in a wide range of fields. Some work on the design and development of new materials for specific purposes. A materials engineer may work in the aerospace industry designing a better material for the outside of a spacecraft. Another may design new stain-proof fabrics, **Figure 7-2**. These engineers often work in corporate or university research labs.

Figure 7-2.

One job for a materials engineer might be to design fabrics that repel stains.

Nano-Tex

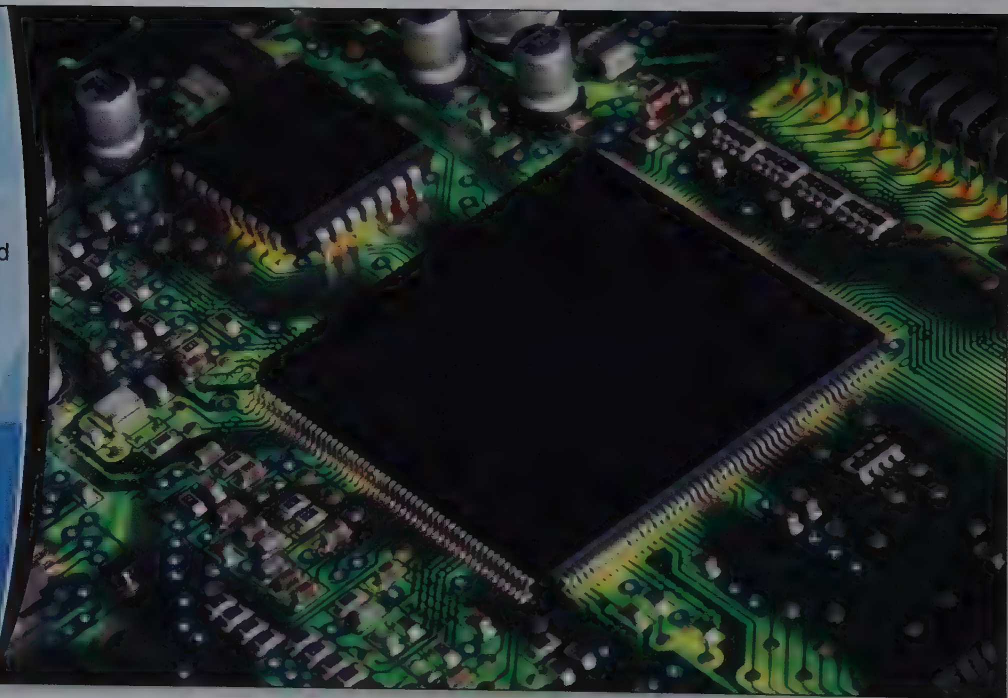

Figure 7-1.

The types of materials used have had a great effect on the Information Age. These materials have been used to create computer chips and other modern devices.

Volodymyr Krasyuk/Shutterstock.com

Materials engineers also work on the manufacturing side and try to find the best ways to produce products using specific materials. For example, a materials engineer may develop a better way to use plastics in the production of children's toys. Another materials engineer may work in biotechnology to determine the best material and manufacturing method for an artificial heart.

Materials engineers often specialize in one type of material. For example, a materials engineer may specialize in plastics, ceramics, metals, or biomaterials. Depending on their job, they may even narrow down their specialization even more. A materials engineer in a civil engineering firm may focus only on asphalt or concrete. See **Figure 7-3**.

Figure 7-3.

Materials engineers often narrow their specializations to one or two materials, such as concrete.

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Professional Aspects

Materials engineers often start their careers with a bachelor's degree in materials engineering. It is also common to earn a bachelor's degree in another field of engineering, such as civil or electrical, with a minor in materials engineering. Students in high school who are interested in materials engineering should take upper-level math and science courses, such as calculus, statistics, chemistry, and physics. In college, materials engineering students take courses in physics, chemistry, calculus, engineering design, thermodynamics of materials, structures of materials, metallurgy, composites, polymers, and material selection. Students will also spend time in internships prior to graduation. Many colleges and universities also offer advanced degrees (master's and doctorate degrees) in materials science and engineering. Another role within the field of materials engineering is a materials engineering technician. Materials engineering technicians conduct material tests, complete projects, and analyze and report test results for materials engineers. The job of a materials engineering technician typically requires an associate's degree in materials engineering technology.

Practicing materials engineers have several professional organizations that represent their interests. One of the largest with over 30,000 members worldwide is ASTM (formerly the American Society for Testing and Materials). One of the main functions of ASTM is the development of material testing standards. When materials engineers need to know the proper way to test a specific material, they reference over 12,000 ASTM standards. Other large professional organizations include the Materials Information Society (ASM International), the Materials Research Society (MRS), and NACE International (formerly the National Association of Corrosion Engineers). There are also a number of associations for materials engineers who specialize in ceramics, plastics, and metals.

Science

The Periodic Table

Materials engineers must understand different types of matter in order to design new and better materials. Matter is made up of elements, which are substances that cannot be broken down into different materials. Some elements are natural, while others have been created over time. All materials comprise different combinations and amounts of the known elements.

There are currently over 100 known elements. Several elements share similarities with other elements, making them easier to group together. The periodic table is an organizational tool for grouping the elements. See **Figure A**. As you can see in the periodic table, the majority of elements are metal.

The periodic table of elements contains certain information for each element. Although some tables may provide more information, there are three pieces of information found in every table. For each element, the atomic number, atomic symbol, and element name is given. See **Figure B**. Other information given in a more detailed periodic table includes the electron configuration and the atomic radius.

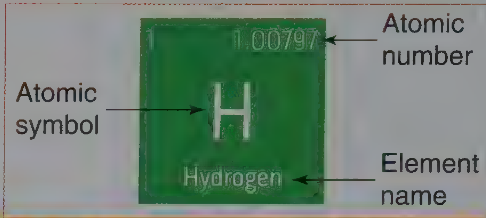

Figure A

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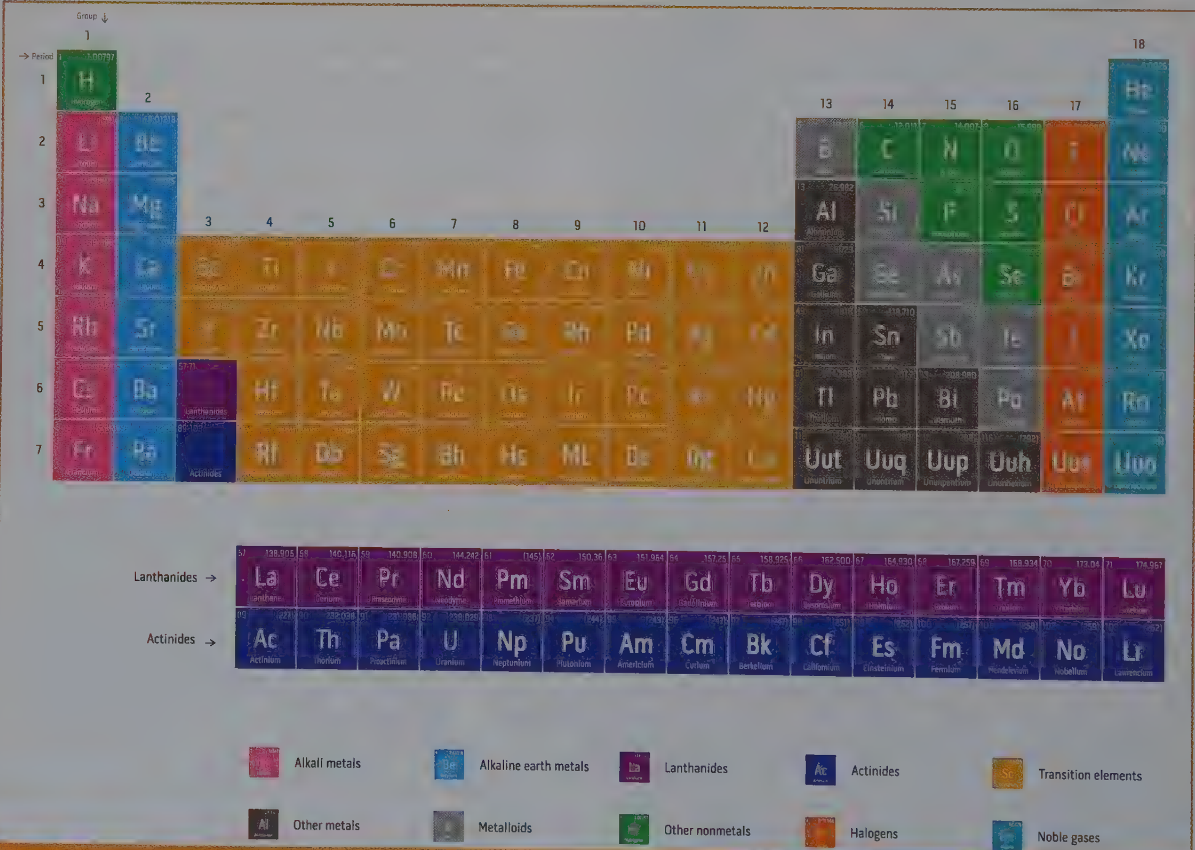

Figure B

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Principles of Materials Engineering

Materials engineering is a broad field of engineering because materials are used in every other field of engineering. Civil engineering, for example, relies on an understanding of construction and building materials. Electrical engineers must understand how to use and manipulate materials that conduct electricity. There are basic principles all engineers must understand about materials. These principles include the types and properties of materials.

Material Types

The most basic knowledge a materials engineer must have is the understanding of the types of materials. Materials can be divided into several categories. The most common way is to divide materials into general classes. These include metals, ceramics, polymers, and composites. See **Figure 7-4**.

Metals

The first category of materials is ***metal***. Metals have been used by humans for thousands of years. Metals are chemical elements that belong to one of the families of metals on the periodic table. Metals are the most common element with over one hundred types of metal on the periodic table. Metals have a crystalline atomic structure. In crystalline structures, the atoms are arranged close together in a regular and repeating structure. See **Figure 7-5**.

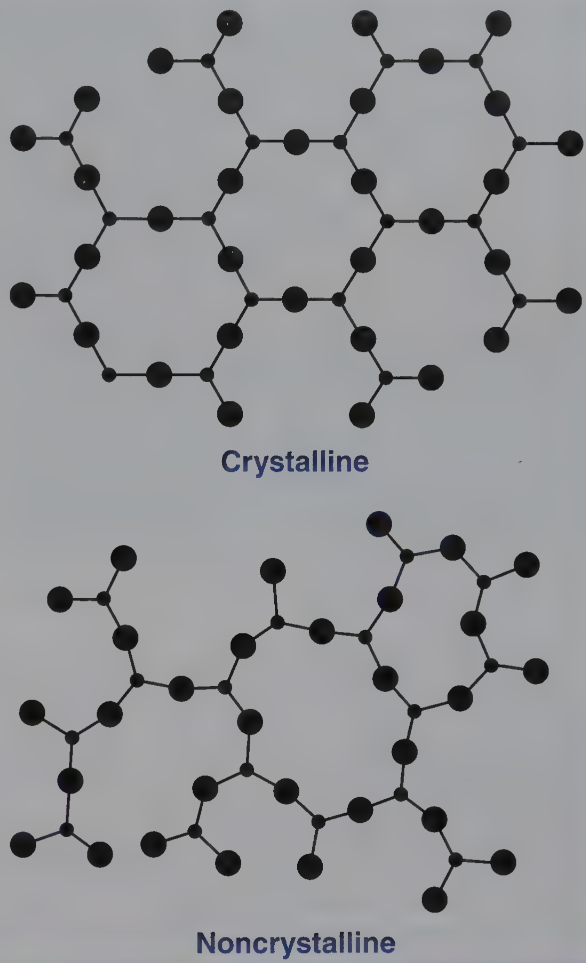

Figure 7-5.

Crystalline materials, such as metals and ceramics, have a regular and repeating structure. Noncrystalline materials, such as polymers, have irregular structures.

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Types of Materials

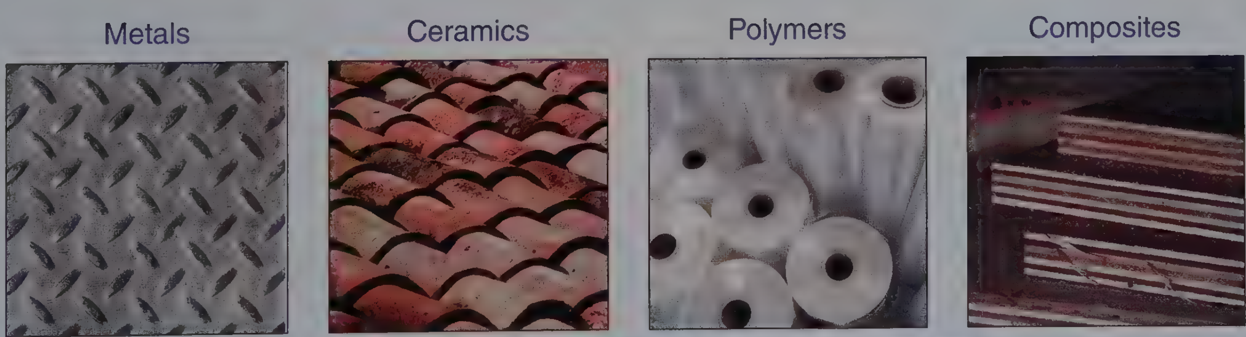

Figure 7-4.

The four types of materials are metals, ceramics, polymers, and composites.

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This creates a strong structure that leads to high material strength. Along with high strength, metals are generally good conductors of heat and electricity and are malleable (able to be shaped).

Metals are an inorganic material, meaning they are not derived from living organisms. Most pure metals are also natural rather than synthetic, meaning they occur in nature rather than being man-made. Many naturally occurring metals (such as iron, aluminum, and tin) are found mixed with other minerals within the surface of the Earth. This rock mixture is known as an ore, **Figure 7-6**. Mining techniques are used to recover the ore. The metals are then extracted from the ore and processed into usable forms of the metal. The processing step usually involves at least heat and pressure, but it may also include the use of chemicals and electricity.

Figure 7-6.
Ore is a naturally occurring rock mixture found within the surface of the Earth. Many metals are found in ore.

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Common metals used in engineered products include iron, copper, aluminum, and titanium. These metals, however, are seldom used in their pure form. Metals are commonly used in alloys. An ***alloy*** is a mixture of a metal with one or more additional elements. Copper is a metal that is used to make two common alloys: brass and bronze. Brass is an alloy made from copper and zinc, and bronze is the combination of copper and tin. Steel is another example of an alloy. It is the combination of the iron and carbon. Steel can be used for a number of applications, depending on the amount of carbon that is added. See **Figure 7-7**. Steel with a low-carbon mixture is often used for general purposes, while high-carbon steel is used for industrial tool and bits. Additional metals can also be added to iron and carbon to make other steel alloys.

Figure 7-7.
Steel is an alloy that can be formed and used for several purposes.

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For example, when chromium is added to steel, it becomes stainless steel. Materials engineers are able to change the properties of the alloys by changing the amount of individual elements that are used. See **Figure 7-8**.

Ceramics

Ceramic is another material type that has been used for thousands of years. Technological and material advances, however, have led to new ceramic materials that could not have been imagined even hundreds of years ago. ***Ceramics*** are nonmetallic solids made from inorganic materials (often minerals). The elements that are used to make ceramics are both metallic and nonmetallic. Ceramics are usually made using a process of mixing, shaping, heating, and cooling. Imagine making a clay pot in art class; you mix the clay minerals with water, shape the pot, dry it, heat it in a kiln, and let it cool. Like metals, ceramics have a crystalline structure. This again makes them strong in compression, but unlike most metals, ceramics are brittle. Ceramics also have a high melting temperature, can retain heat well, but are not good conductors of electricity. This makes most ceramics good insulators.

There are several common types of ceramics. Clay, as described above, is an example of one of the first uses of ceramics. Clay can be used to make bricks and roof tiles, **Figure 7-9**. Cement, plaster, and gypsum are also examples of ceramic materials. These materials have long been used in construction. Many types of abrasives are also ceramic materials. Garnet, silicon carbide, and tungsten carbide are all abrasives that are used in products such as sandpaper and grinding wheels. Refractory materials are ceramics that are used in high-temperature applications, **Figure 7-10**. Magnesium oxide is a refractory material that is used as an industrial insulator, in heating elements, and as a fireproofing material. Some ceramic materials have properties that are different from most other ceramics. Like metals, most ceramics have a crystalline structure. Glass is the only ceramic material to have a different internal structure. There are also ceramic materials that can become magnets either permanently or when voltage is applied.

Figure 7-9.

Ceramic materials were used to make the tiles on this roof.

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	Carbon Steel		Alloy Steel
Name	Low-carbon and mild steel	High-carbon steel	Stainless steel
Composition	0.05%–0.29% carbon	0.6%–0.99% carbon	10.5%–30% chromium
Properties	Inexpensive, malleable, low tensile strength	Very strong and hard	Resistant to corrosion and oxidation
Uses	Structural steel, car manufacturing, road signs, common wire	Springs, high-strength wire, cutting tools	Cookware and utensils, surgical instruments, decorative features

Figure 7-8.

This table shows the composition, properties, and uses of different types of steel. Materials engineers can change an alloy's properties and, therefore, its uses.

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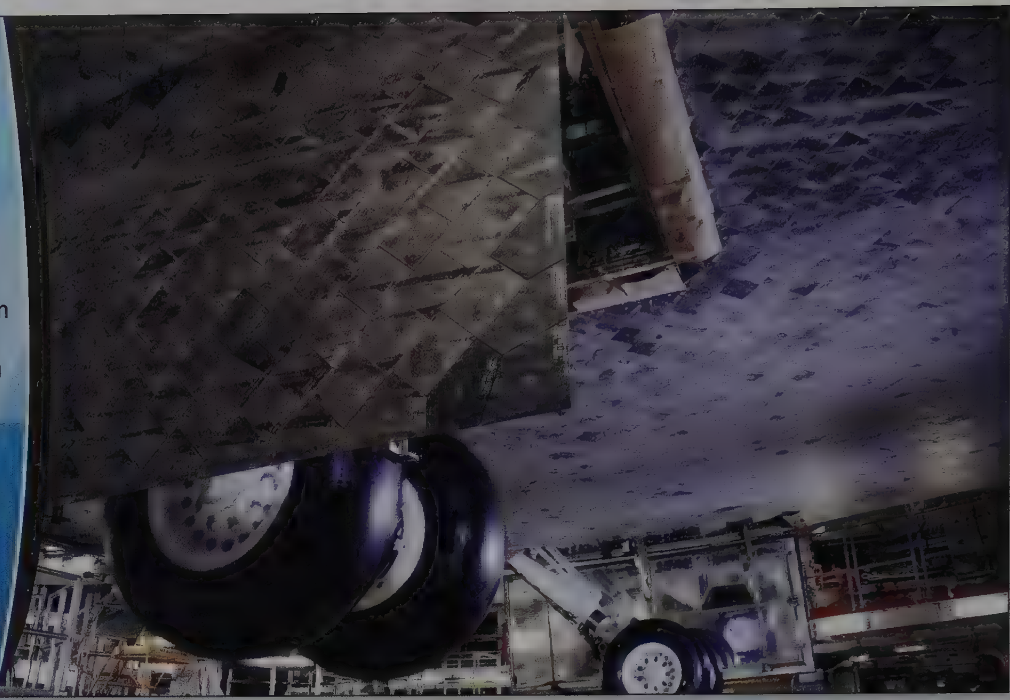

Figure 7-10.
The tiles on the space shuttle shown are made from a type of ceramic material that is able to withstand high temperatures.

NASA

Polymers

Polymers are materials that are made up of a long chain of small molecules that form a much larger molecule. The molecules often include carbon and hydrogen atoms. Polymers are organic materials because carbon is an organic element. They are also noncrystalline, unlike metal and ceramics. Polymers can be natural or synthetic. Natural rubber, cellulose, starch, and proteins are all examples of natural polymers. Synthetic polymers, however, are much more common. Plastics are the most common type of synthetic polymer.

It is difficult to go through your day without coming in contact with plastics, **Figure 7-11**. Plastics are made from the by-products of refining petroleum to make oil and gasoline. Plastics have a number of favorable properties. They are lightweight but strong, as well as easy and fairly inexpensive to process. They can also be used to make thousands of different products. Plastics do have some negative impacts, including environmental impacts.

There are two main types of plastics: thermoplastic materials and thermoset materials. See **Figure 7-12**. Thermoplastic materials can be heated, reshaped, and cooled numerous times.

Figure 7-11.
We use plastic products every day. Plastics are lightweight and inexpensive but durable.

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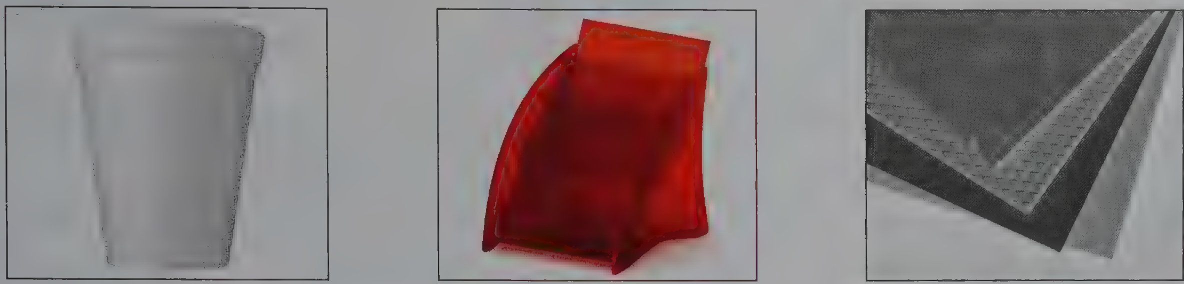
Thermoplastics



Thermoset Plastics

Figure 7-12.

Plastics are used to make many different products. Thermoplastics and thermoset plastics are the most common types of plastics.

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Going Green

Recycling Plastics

The use and disposal of materials is of great concern to materials engineers. This is especially true of plastics. Both the creation and disposal of plastics are harmful to the environment. The creation of plastics is worrisome as they are made from oil and natural gas, which are exhaustible resources. The disposal of plastics is harmful because they will essentially never biodegrade. This means that once a plastic product is produced, it will exist forever. That is, it will exist unless the plastic product is recycled and used to make other products. Recycling plastics saves the use of oil and natural gas, and those plastics do not take up space in landfills.

In an effort to help plastics manufacturers, consumers, and recycling companies, the Society of the Plastics Industry created a coding system that would help to identify and sort different types of plastics. These codes are printed or stamped on nearly all plastic products and consist of the recycling symbol, a number, and an abbreviation. The codes are useful to consumers who recycle plastic products because not all recycling programs will accept all types of plastics. Many communities have curbside or drop-off recycling programs that recycle a range of plastics and paper products. Because of these types of programs and a general concern for the environment, over 82 million tons of materials are recycled per year in the United States. This represents nearly one-third of the total waste produced in the United States.

Common thermoplastics include polyethylene (plastic bags), polyvinyl chloride or PVC (pipes), polystyrene (foam cups and CD cases), and acrylonitrile-butadiene-styrene or ABS (Lego® building blocks). Thermoset plastics have very strong chemical bonds and cannot be reshaped when heated. These are often used for higher heat and permanent applications. Thermoset plastics include most polyester resins (fishing rods), epoxy (coatings and adhesives), and silicone (sealant). The first synthetic plastic, named Bakelite, was a thermoset material (phenol formaldehyde resin) created in 1907.

Composites

Metals, ceramics, and polymers have a number of uses. However, they are not suitable for all potential applications. Often a new material is needed to utilize the advantages of several materials. These materials are known as composites. ***Composites*** are materials that combine two or more materials. In composites, each material can be identified. For example, concrete is a composite of cement, gravel, rocks, and water. If you were to break apart a concrete sidewalk, you could identify the gravel, rock, and cement. Like polymers, composites can be either natural or synthetic.

The most common natural composite is wood. Wood is a combination of cellulose fibers and organic lignin resins. The cellulose fibers are natural polymers that make up most of the tree. The fibers create the grain of the wood. The cellulose fibers are held together by the lignin resins, which act like an adhesive material. Wood is used in many fields of engineering and is even used in other composites to lessen some of the disadvantages of wood.

Synthetic composites have been used for a number of years and include many of the advanced materials that we use today. Using wood as an example, plywood is a composite. Plywood is made up of thin strips of wood that are layered together with adhesive. See **Figure 7-13**. One disadvantage of wood is that is loses its strength depending on the orientation of the grain. In plywood, however, the wood grain of each layer runs in perpendicular directions, making plywood very stable.

Figure 7-13.

Plywood is one type of composite. This composite combines strips of wood and adhesive.

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Most composites have one material that is placed within another material to provide additional strength. The main material is known as the matrix and the strengthening material is called the fiber. For example, in reinforced concrete, the concrete is the matrix and the steel rods are the fiber. In fiberglass, one of the first composites that used synthetic polymers, the polymer (or plastic) is the matrix and the strands of glass are the fibers, **Figure 7-14**. Composites have made great impacts in a number of engineering fields.

Figure 7-14.

The strengthening material inside this plastic helmet is its strands of glass.

OZaiachin/Shutterstock.com

For example, carbon fiber–reinforced polymers have impacted transportation. Vehicles including bikes, airplanes, and automobiles use carbon-fiber elements because they provide high strength at a low weight. Carbon-fiber uses epoxy as the matrix and strands of carbon as the fiber material.

Other Materials

Not all materials that are used in engineering can be placed in one of the four previous categories. Two of those materials include fluids and semiconductors. Fluids are not necessarily viewed as an engineering material. However, many engineered products rely on the use of fluids to operate. So, engineers must have an understanding of their uses and properties. The two most common fluids are air and water, **Figure 7-15**. Air can be used to heat and cool. For example, an engineer who is designing a refrigeration unit must understand how the cool air will flow through the system. Engineers designing pneumatic and hydraulic tools that use air and water or oil to transmit power must understand how those fluids operate. At the most basic level, imagine what would happen if an engineer designed a swimming pool without considering the weight and pressure of the water that the pool would hold.

Semiconductors are another type of material that does not fit into one of the previous categories. Semiconductors are elements and compounds that can act as either insulators or conductors. Silicon and germanium are two elements that are semiconductors. Semiconductors are used to create electronic components such as microprocessor chips, transistors, diodes, and light emitting diodes (LED). See **Figure 7-16**. These components are described in greater detail in Chapter 8 and Chapter 12.

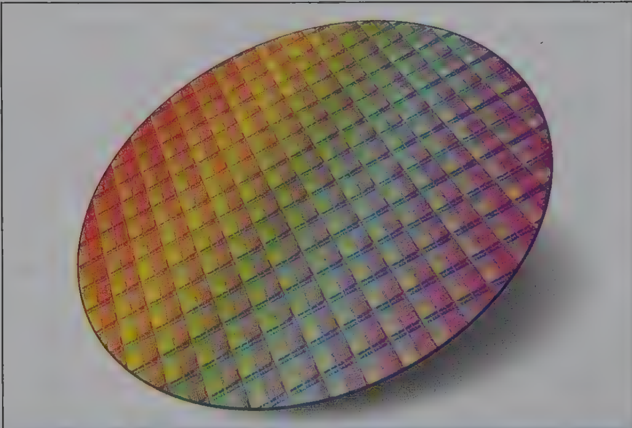

Figure 7-16.
Silicon wafers are semiconducting materials that serve as the substrate for microprocessors.

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Figure 7-15.
In order to design this water pumping station, engineers must have an understanding of fluids.

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Design

Materials Symbols

In the world of design, attempts are always made to display as much visual information as possible. This is especially true in architecture, and a number of standard symbols have been created to designate everything from doors to toilets.

This is also true for the materials that are used. Symbols exist for common building materials, such as brick, concrete, and cinder block. There are also symbols for different types of insulation, glass, and metal. See **Figure A**. These symbols allow designers and architects to include graphics of the types of materials that are to be used.

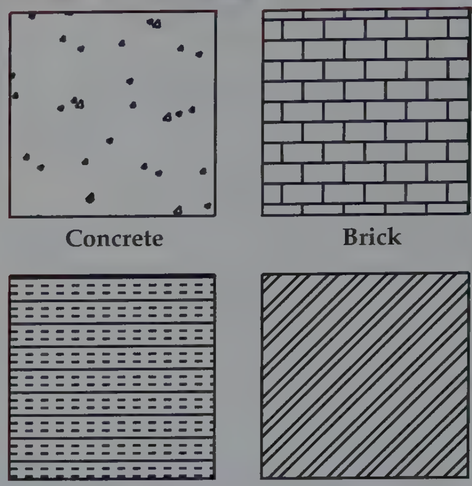

Figure A.

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These devices (and the use of semiconductors) have revolutionized the electronics and computer industries. The computing power that is possible today is due to the use of semiconductors.

A newer material being focused on by an increasing number of materials engineers is biomaterial. A ***biomaterial*** is a substance that interacts with living systems. Scientists and engineers design and develop biomaterials that can safely and effectively interact with the human body. Biomaterials are used in medical applications, such as organ transplants, heart surgery and repair, pharmaceutical drug delivery, and tissue repair.

Material Properties

Materials engineers must have a good understanding of not only the types of materials, but also of the material properties. All materials have certain properties. For example, aluminum is lightweight, concrete is strong in compression, iron rusts when exposed to water and air, and bricks have a high melting point. These are all examples of material properties. Materials are used in engineered designs based on their properties. Electrical wires are not made out of clay, because it is not a good conductor of electricity. Copper is a good conductor of electricity, so it is used. All materials have applications for which they are better suited than others. There are six categories of material properties presented in this chapter: physical, mechanical, electrical and magnetic, chemical, thermal, and optical and acoustical.

Physical Properties

Physical properties of materials are the most basic qualities of a material. Often the physical properties can be obtained using our senses. We can observe the size and shape, the look and feel, and the taste and smell of a material, **Figure 7-17**.

Figure 7-17.

The various shapes and sizes of materials are examples of physical properties.

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These are all examples of important physical properties. These may be more important in some application than in others. The taste of a plastic used in the design of a laptop case is not as important as the taste of a newly designed food additive.

Other physical properties are not able to be determined using our senses. The most commonly used is density. Density is a physical property related to the mass of an object. Density, in mathematical terms, is the mass per unit of volume and is often measured in kilograms per cubic meters (kg/m^3). The formula for density is as follows:

$$D = m/v$$

Mass is the amount of matter in an object. Volume is the amount of space that a material occupies. So, density is the amount of matter within a specific amount of space. The higher the density, the more tightly packed the material. An object's density is often used to compare materials.

Imagine a 12 oz (335 cm^3) bottle of water filled with different materials. If filled with water, it would have a mass of 354 grams (0.78 lbs). This is calculated using the formula $m = D \times v$. The known density of water at room temperature is 997 g/cm^3. By multiplying the volume (997 g/cm^3 × 335 cm^3), we are able to calculate the mass of 354 grams. If it were filled with mercury, the mass would be much greater because mercury is denser than water at 13570 g/cm^3. The mercury would have a mass of 4815 grams (10.62 lbs.) because 13570 g/cm^3 × 335 cm^3 = 4815 grams. Generally, most materials that are less dense than water float in water.

Mechanical Properties

Mechanical properties determine how a material behaves when a force or load is applied. This includes how much a material bends, how much it can be stretched, and how much weight it can hold before it breaks. The idea of strength may come to mind, but you will find that there are several types of strength. When describing the mechanical properties of a material, it is important to understand stress. ***Stress*** is the amount of force or load that is applied to a material. The force can be applied through an axis of the material, or axial load, **Figure 7-18**. The axial load can be a compression force (tightening a piece of metal in a vise) or tensile force (pulling on both ends of a cable). ***Compression strength*** is the ability of a material to withstand a load that compresses or squeezes the material. For example, imagine you step on a piece of foam, then a piece of wood. The wood would demonstrate higher compression strength. ***Tensile strength*** is the ability of a material to withstand a force that pulls the material apart. If you were to pull on both ends of a wire cable and a fishing line, the wire cable would demonstrate higher tensile strength. When the stress is not applied through an axis, it is shear stress. ***Shear stress*** is a bending or twisting force, like the stress that occurs when using a wrench.

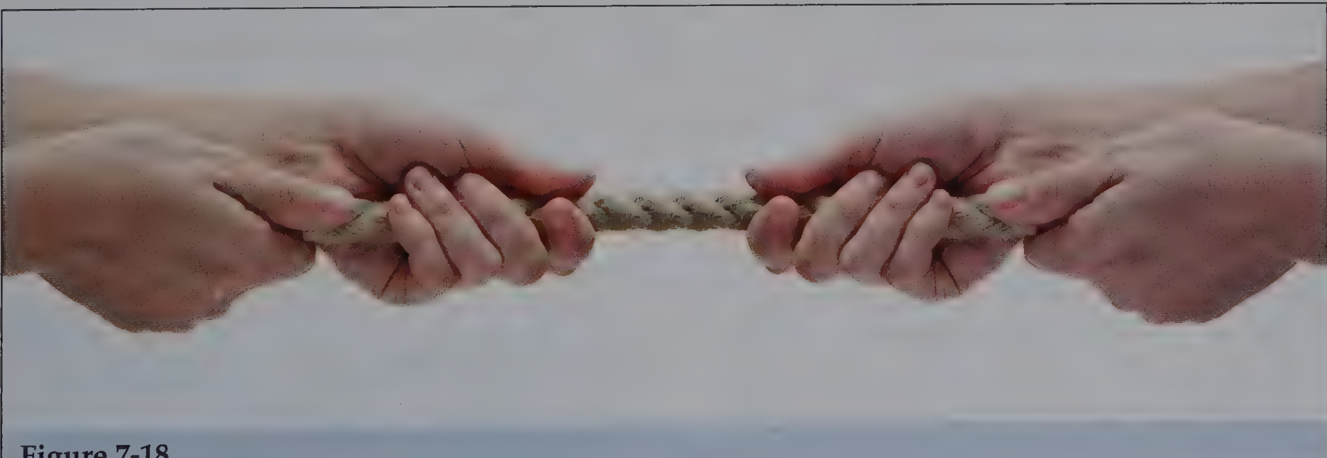

Figure 7-18.

Pulling a rope in opposite directions is an example of the tensile force of an axial load.

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When stress is applied to a material, it will deform until it breaks. The deformation that occurs from stress is known as strain. ***Strain*** (ε)can be determined by dividing the amount of deformation (δ) by the original length of the material (L). The following is the formula to determine strain:

$$\varepsilon = \delta / L$$

Imagine you had a 2 m (2000 mm) steel rod that was deformed so it was now 2003 mm in length. The total deformation would be 3 mm. To calculate the strain, you would divide the amount of deformation (3 mm) by the length of the material (2000 mm). The equation is:

$$\varepsilon = 3\text{ mm} / 2000\text{ mm}$$
$$\varepsilon = 0.0015$$

Math

Equations

When working with formulas, you may need to rearrange the formula to solve for a specific variable. For example, imagine you need to determine how much a 6 mm piece of metal would deform when presented with an amount of 0.003 strain. The common formula for strain is written as:

$$\varepsilon = \frac{\delta}{L}$$

In this case, the formula would be:

$$0.003 = \frac{\delta}{6\text{ mm}}$$

However, you want to solve for δ, so you need to rearrange the formula. Rearranging a formula for this purpose is known as isolating a variable. When you isolate a variable, your goal is to have the unknown variable on one side of the equals sign and the known variables on the other side. In this example, the goal is to have the amount of deformation on one side and strain and length on the other. To isolate a variable, you must perform the opposite function on each of the variables that you are trying to move. You must do this on each side of the formula. In this example, you are trying to isolate δ. This means you need to move the L variable. It is meant to divide the δ variable, so you multiply it on both sides of the equation.

$$0.003 = \frac{\delta}{6\text{ mm}}$$

$$6\text{ mm} \times 0.003 = \frac{\delta}{6\text{ mm}} \times 6\text{ mm}$$

$$6\text{ mm} \times 0.003 = \frac{\delta}{\cancel{6\text{ mm}}} \times \cancel{6\text{ mm}}$$

$$6\text{ mm} \times 0.003 = \delta$$

$$0.018\text{ mm} = \delta$$

Isolate the variables as directed in the following equations.

1. Isolate the variable ΔT in the equation $\alpha_L = \Delta L / L \times \Delta T$
2. Isolate the variable L in the equation $\varepsilon = \delta / L$
3. Isolate the variable v in the equation $D = m / v$

Strain occurs in a material once the stress is applied until the point at which it breaks, known as the fracture point. Before a material reaches the fracture point, it will go through two phases. See **Figure 7-19**. This can be demonstrated graphically in a stress/strain diagram. In the first phase the material is being stretched, compressed, or twisted but not enough to be permanently deformed. This is known as a material elasticity. ***Elasticity*** is the ability to return to the original dimensions if the stress is removed. Elasticity ends at the yield point. The yield point can be calculated by dividing the amount of stress by the amount of strain.

Any stress applied after the yield point will cause permanent deformation to a material. The deformation that occurs from the yield point to the fracture point is known as plastic deformation, or ***plasticity***. See **Figure 7-20**. The amount of plastic deformation that occurs in a material is used to determine two additional mechanical properties: ductility and brittleness. A material that has a high ductility can withstand a considerable amount of deformation before fracturing.

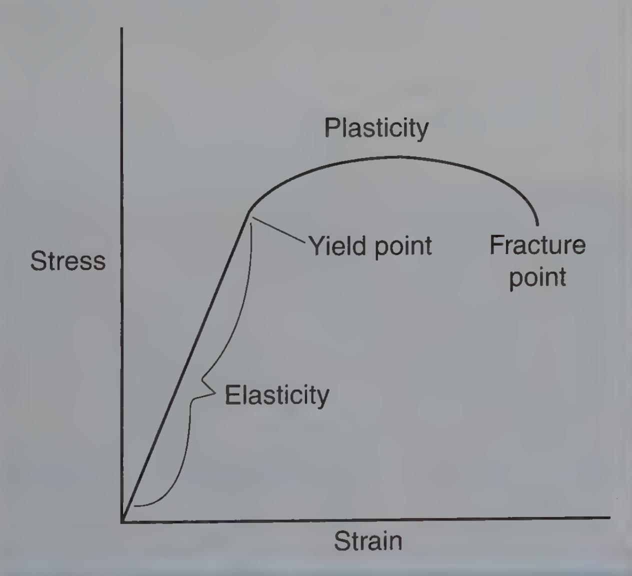

Figure 7-19.

When stress is applied to a material until it breaks, it goes through various phases. A material has elasticity up until its yield point. Stress after the yield point is plastic deformation. Plastic deformation occurs until the fracture point, when the material breaks.

Goodheart-Willcox Publisher

Figure 7-20.

Plastic deformation occurs before the fracture point. This material has been permanently deformed, but it is not yet fractured.

Lincoln Rogers/Shutterstock.com

Copper is an example of a ductile metal, which is why it is used for wiring. A material that cannot withstand plastic deformation is considered brittle. Glass is a brittle material because it deforms very little before it fractures.

Other mechanical properties include hardness and toughness. These two properties are often confused, but are distinctly different. Material hardness is a material's resistance to scratching. For example, the metal zinc can be more easily scratched than a diamond, making the diamond a harder material. Material toughness is the resistance to a sudden impact. Think of hitting a material with a hammer. The higher the toughness, the less impact the hammer would make. It is not hard to believe that iron is more tough than clay. Toughness is sometimes known as impact strength.

Electrical and Magnetic Properties

Electrical and magnetic properties relate to how a material behaves when electrically charged or within a magnetic field. The understanding of the electrical properties (how materials behave when electrically charged) helps engineers place materials in one of three categories: conductors, insulators, and semiconductors. Conductors are materials that allow for the movement of electricity through the material.

Copper, silver, and gold are all good conductors, **Figure 7-21**. Insulators (or resistors) are materials that do not provide good movement of electricity. Glass and other ceramics and plastics are good insulators. Semiconductors are materials that fall between conductors and insulators.

There are two main electrical properties; conductivity and resistivity. ***Conductivity*** is the measurement of how well electricity flows through a material. ***Resistivity*** is the measurement of how well a material resists the flow of electricity. They are both measured in ohm meters (Ω-m). The two properties are reciprocal, meaning if a material has a high conductivity it would have a low resistivity. Both properties are usually reported with the material at 20°C. A change in material temperature can have a large impact on the material's ability to conduct electricity. Principles of electricity are described in greater depth in Chapter 8.

The magnetic properties of materials are based on their magnetic permeability. Magnetic permeability is how a material acts when placed in a magnetic field. This can be thought of as similar to the concept of conductivity. If the magnetic permeability is high, the material will allow magnetic flow (or flux). This means that the material will become magnetized and will either be attracted or repel the magnetic field. Permeability (μ) is measured in Henrys per meter.

Permeability of a material is impacted by factors such as temperature and distance from the magnetic field. Elements such as iron, cobalt, and nickel are known as ferromagnetic materials and are the strongest natural magnetic elements.

Chemical Properties

Chemical properties are those properties that are changed by a chemical reaction. In many cases, engineers attempt to control chemical properties because they are often damaging to the material. Chemical properties include flammability and corrosion. ***Flammability*** is the ease at which a material will ignite. ***Corrosion*** is a reaction between a material and the environment that leads to deterioration of the material. Corrosion is a natural process that is common in metals. The most common example is the oxidation (or rusting) of iron. See **Figure 7-22**. When iron is exposed to oxygen and water, a chemical reaction forms with the iron. The result of the reaction is an iron oxide that damages, and consumes, the iron. Rust has been estimated to have caused billions of dollars in damage to bridges and other structures in the United States alone. Some materials are so prone to oxidation that they have to be coated with protective finishes before they can be used in products.

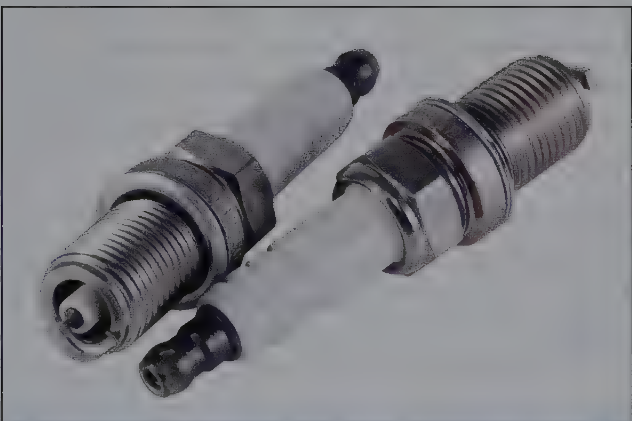

Figure 7-21.

Materials that are conductors, such as those found in this spark plug, provide good movement of electricity.

OlegDoroshin/Shutterstock.com

Figure 7-22.

Corrosion, such as the oxidation of iron, leads to a material's deterioration.

Ilya Andriyanov/Shutterstock.com

Thermal Properties

Thermal properties include those material properties that are related to how the material responds to heat. These include thermal conductivity, resistivity, thermal expansion, and melting point. ***Thermal conductivity***, like the other types of conductivity that have been discussed, is determined by how well heat is transferred through the material. If you have ever stirred a pot on a stove with a metal spoon and felt the spoon heat up, you have experienced thermal conductivity. Thermal conductivity is usually expressed in watts per meter Kelvin (W / m × K). The formula takes into account the rate of energy conversion, temperature, and thickness of the material. Metals are better thermal conductors than other materials. Similar to electricity, the reciprocal of thermal conductivity is thermal resistance. ***Thermal resistance*** is expressed by an R-value. R-values are commonly used to describe the insulation values of building materials. See **Figure 7-23**. For example, if you were insulating your attic, you may choose an insulation value between R-30 and R-38. The higher the R-value, the less heat flows through the material. Ceramics and a number of polymers are good insulators.

Another thermal material property is thermal expansion. Due to thermal expansion, most materials change size when they are heated and get smaller as they cool. A coefficient of thermal expansion for a material (α_L) is determined by dividing the change in length of the material (ΔL) by the original length (L) multiplied by the change in temperature (ΔT). The following is the formula to find thermal expansion:

$$\alpha_L = \Delta L / L \times \Delta T.$$

Engineers can use premade charts to determine the coefficient of thermal expansion for their specific applications. For example, if a land surveyor uses a 300′ steel tape to measure a piece of property in 20°F weather, and then measures the same property in 80°F, there could be a significant difference in measurements. To determine the difference, the surveyor uses the formula $\Delta L = \alpha_L \times L \times \Delta T$. In this example, the coefficient of thermal expansion of steel is 0.0000073 in/in °F, the length is 300′ (3600″), and the change in temperature is 60°F. The formula is:

$$\begin{aligned} \Delta L &= 0.0000073 \text{ in/in °F} \times 3600'' \times 60\text{°F} \\ \Delta L &= 1.57'' \end{aligned}$$

Figure 7-23.
The R-value for this insulation determines the amount of heat that will flow through it.

Christina Richards/Shutterstock.com

Without determining the amount the tape contracted, the measurements may be incorrect.

The ***melting point*** of a material is the temperature at which the material changes from a solid to a liquid. Metals, such as iron and nickel, have melting points of over 2600°F.

Optical and Acoustical Properties

Optical and acoustical properties determine how light and sound waves interact with materials. Materials vary on how well they absorb, reflect, or transmit light and sound. When light hits a material, generally some of the light is absorbed by the material and is turned into heat energy and some of the light is reflected. The reflected light is what gives the material a color. For example, if a material absorbs all of the light except that of the blue wavelength, the material will appear blue. Transparent materials also absorb and reflect light, but they also allow some light to pass through. This is known as transmission.

Sounds can also be either absorbed or reflected by a material. Porous materials are more likely to absorb sound. Smooth materials generally reflect sound in one direction, and materials that are rough reflect sound in many directions. Concert halls use a range of materials to absorb sound (too much reflection can cause an echo) and to reflect sound in numerous directions to make the sound seem more full. See **Figure 7-24**.

Figure 7-24.

One type of acoustical property determines how much sound is absorbed or reflected by a material. For example, soundproofing material does not let sound pass through.

Tony Robinson/Shutterstock.com

Another acoustical property includes how well the material transmits vibration. This is important in such applications as acoustic guitars. Imagine how different a guitar made from plastic or metal would sound. Even when using wood, there is a great sound difference between different species of wood.

Material Engineering Applications

Materials engineers and scientists use knowledge of types and material properties in a number of applications. Two applications are material testing and nanotechnology.

Material Testing

When engineers and designers create new products and improve existing products, they often use new and different materials. An automobile designer, for example, may use a new material for a car bumper that is lighter but resists denting better than a previous material. Other times, the designer may try to use a different formulation of the existing material. For example, a container company will try to make the best water bottle they can with the least amount of material. In order to determine the how much plastic to use to make the water bottle or the best material to use for a bumper, the material must be tested.

Material testing is a large industry in which many companies specialize in specific materials. A material testing company may test only construction materials, plastics, or even adhesives or paints. The ASTM organization is the leader in developing standards for testing materials. If engineers want to analyze the chemical composition of limestone or if they want to test the impact strength of cast iron, they find the procedures for those tests in the ASTM library. All material tests belong to one of two main categories of materials tests: destructive tests and nondestructive tests.

Destructive Tests

Destructive material tests are tests that destroy a material or somehow make a material unusable. Destructive tests are often used to test a material's mechanical or chemical properties.

Destructive tests that test mechanical properties usually exert a force on a material until it fails. The amount of force is measured to determine the mechanical properties such as elasticity, deformation, yield point, and ultimate strength. Common examples of these tests include tensile tests that introduce a pulling force, compression tests that use a pushing force, and fatigue tests that use reciprocating forces (like opening and closing a door repeatedly). See **Figure 7-25**. These tests are often performed on small material samples. However, destructive tests can also be performed on full-scale prototypes. An automobile crash test is a destructive test used to measure how well either the entire vehicle or the one vehicular component responds to an accident. Destructive tests used to measure chemical properties usually test the material's reaction to a corrosive material or environment. For example, a material that is going to be used as a hull of a ship (or the coating that will cover the material) would be exposed to saltwater to test how it will react. Imagine the tests materials used in the space program go through in the design of spacecraft.

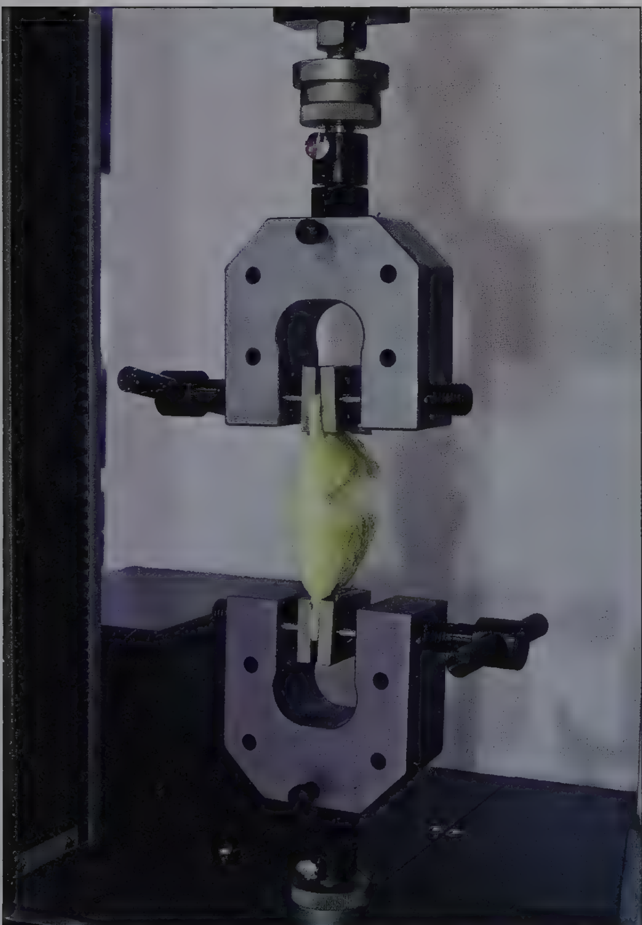

Figure 7-25.

Destructive tests, such as fatigue tests, are often used on small material samples.

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Nondestructive Tests

Nondestructive material tests are tests that leave the material intact and do not destroy the material. These tests are often used to inspect the materials and to look for flaws and defects in the materials. These tests are not only conducted on materials, but can also be used for the testing of products in use. Bridges, pipelines, airplane wings, and boat hulls are maintained using nondestructive tests. The simplest example of a nondestructive test is a visual examination. In a visual test, an engineer examines a material to see if there are any surface defects, cracks, or voids in the material. This could be done with the naked eye or by using a microscope, depending on the material. In other tests, dyes are used to make the flaws and surface cracks more visible. See **Figure 7-26**. However, in many cases, visual inspections are not detailed enough to determine if there are flaws in the materials.

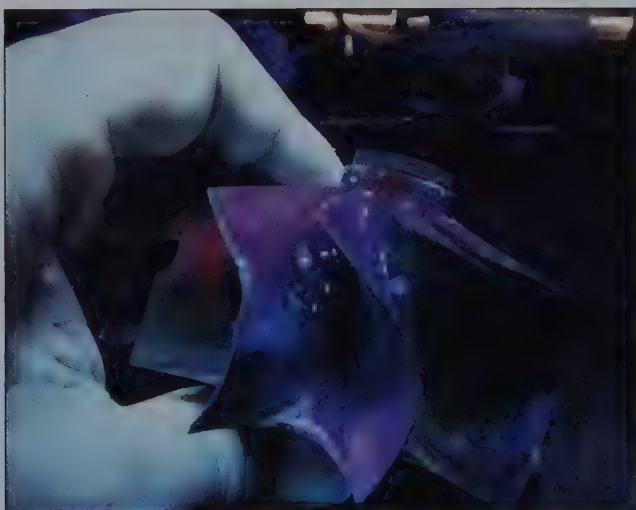

Figure 7-26.

A visual examination is an example of a nondestructive test. Dyes are often used to help examine materials to make any flaws more visible.

Courtesy Aqualified

Other nondestructive tests use waves and currents to determine internal flaws or imperfections. Radiography and ultrasonic tests use waves. These tests may be familiar to you from the field of medicine. These are commonly used in medicine to "look inside" the human body. ***Radiography tests*** use x-rays that pass through the material, and ***ultrasonic tests*** use sound waves that "bounce off" changes in the material to determine the internal composition of a material. See **Figure 7-27**. Electrical and magnetic currents are used in eddy current and magnetic particle testing. Eddy current testing uses a coil that produces an electromagnetic field. When the coil is passed over a conductive material, a magnetic field in the material is produced and measured. Changes in the magnetic field indicate variations or imperfections in the material. Surfaces such as airplane wings and tubing such as pipes are commonly tested using eddy current tests. In magnetic particle testing, a magnetic field is introduced to a material, and iron particles are used to determine if there are internal flaws. The iron particles will build up in areas that contain flaws.

Nanotechnology

Engineers, scientists, and researchers from a number of different fields, including many from materials engineering are now studying nanotechnology. ***Nanotechnology*** is the design of new materials and devices at the scale of a nanometer. A nanometer (nm) is one billionth of a meter. A human hair is actually 25,000 nm wide. Nanotechnology has some potentially exciting impacts, including being able to deliver medicines directly to a cancerous tumor, creating microscopic computer chips, and manufacturing materials that repair and clean themselves.

Nanoparticles

The most basic component at the nanoscale is the nanoparticle. ***Nanoparticles*** are typically between 1 nm and 100 nm in size. See **Figure 7-28**. In materials engineering and materials science, nanoparticles are interesting because at the nanoscale, some materials demonstrate properties that are not present at larger scales. For example, nanoparticles of gold

Figure 7-27.
Ultrasonic tests are used to find imperfections in a material. Sound waves help determine a material's internal composition.

Courtesy Aqualified

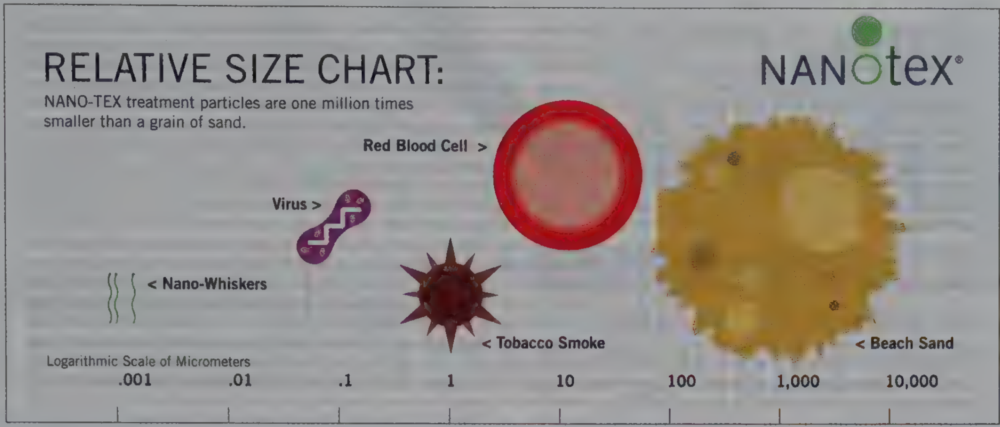

Figure 7-28.

A nanometer is one billionth of a meter. Nano-whiskers are small fibers between 1 nm and 15 nm in width and are often used in textiles.

Nano-Tex

are red and melt at room temperature, copper and zinc become transparent as nanoparticles, nanoparticles of silicon become conductors rather than insulators, and silver nanoparticles have antibacterial properties. Engineers and scientists have been designing products that utilize these properties of nanoparticles. Some food packaging contains silver nanoparticles to control the growth of bacteria, and nanoparticles are used as coatings on fabrics to make them water resistant.

Nanostructures

New structures and materials can also be created with the use of nanotechnology. Several nanostructures are currently being developed as the building blocks of nanotechnology products. These include nanowires, nanotubes, and buckyballs.

Nanowires are small strands of material that range from 1 nm–60 nm in width. Nanowires are currently either stretched to be made thinner, or they are grown in a laboratory. Common nanowire materials include silicon, zinc oxide, tin oxide, and aluminum nitride. Nanowires can be designed to transmit either light or electricity (often without generating heat) and may be useful in computer circuits and lighting applications.

Nanotubes are nano-sized cylinders of carbon. See **Figure 7-29**. Because they are made entirely of carbon, they are a type of material known as fullerene. Nanotubes are a cylindrical fullerene and have a honeycomb pattern. Carbon nanotubes are extremely lightweight but very strong. They are much lighter and much stronger than steel. They are also flexible and can be created to be more conductive than copper. Carbon nanotubes can be created in a typical chemical lab. These properties make carbon nanotubes useful in electronics and structural applications.

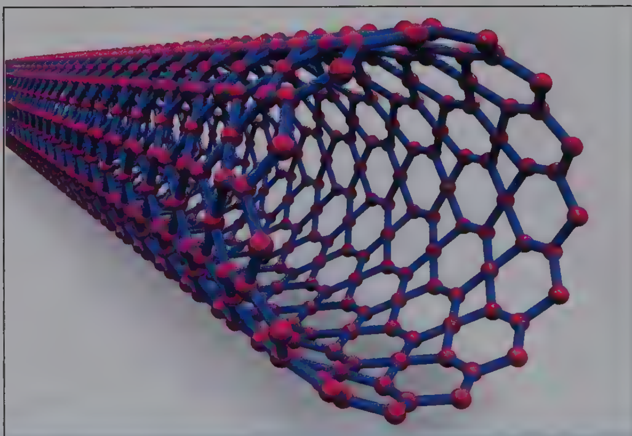

Figure 7-29.

Nanotubes are cylinders of carbon. They are lightweight, flexible, strong, and can be more conductive than copper.

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History

History of Batteries

One of the most standardized components that consumers use is batteries. Whether you need several AA batteries to operate a handheld game console or several D batteries for a flashlight, they are easy to find and replace because their sizes are standardized. However, while the outsides are standardized, the materials on the inside may be very different depending on the type and brand of battery. Advances in material science and engineering have led to better batteries. All batteries essentially do the same thing, convert chemical energy to electricity. Over the past 200 years, new materials and variations of materials have been used to create an electrical current. The materials that are in the batteries determine the voltage, battery life, cost, and weight.

Several of the more common non-rechargeable batteries include zinc-carbon, alkaline, lithium, and silver-zinc batteries. Zinc-carbon and alkaline batteries are the most common for general consumer applications. Zinc-carbon batteries are the least expensive and often come with products that have batteries included. They are constructed of an outer shell that is made of zinc, a carbon rod that serves as the positive terminal, and an acidic electrolyte between the two materials. Most name-brand consumer batteries are alkaline batteries. Alkaline batteries use zinc, manganese dioxide, and an alkaline electrolyte. Lithium and silver oxide batteries are more expensive than either zinc-carbon or alkaline, but last longer and are often used in electronic and medical devices.

Common rechargeable battery types include lead-acid, nickel-cadmium (NiCad), nickel-metal hydride (NiMH), and lithium-ion batteries. Lead-acid batteries were the first commercial rechargeable battery and are commonly used in automobiles. Lead-acid batteries are comprised of lead plates in a container of sulfuric acid. These batteries are heavy compared to other rechargeable batteries. Nickel-cadmium (NiCad) batteries, which use nickel oxide hydroxide and cadmium, became the standard rechargeable battery for cordless tools. In recent years, lithium-ion batteries have begun to replace NiCad and NiMH batteries in many uses. Lithium-ion batteries are constructed using carbon, a metal oxide (such as lithium cobalt oxide), and lithium salts. Lithium-ion batteries are commonly used in laptops, MP3 players, and even electric and hybrid cars.

Another type of fullerene used in nanotechnology is commonly known as a buckyball. A ***buckyball*** is a carbon sphere made up of a series of hexagons and pentagons, similar to a miniature soccer ball. See **Figure 7-30**. It is officially named *buckminsterfullerene*. It is the most perfectly round molecule known to man. That feature makes buckyballs useful as lubricant. Buckyballs are extremely strong and hollow, which makes them a perfect "carrier" for other atoms or nanoparticles. Researchers are experimenting with using buckyballs to carry medicine to specific cells in the human body.

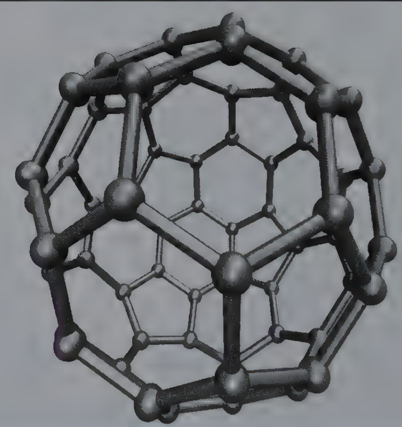

Figure 7-30.

Buckyballs are made up of hexagons and pentagons, giving them the appearance of soccer balls.

Mark Lorch/Shutterstock.com

Nanotechnology is relatively new to the scientific and engineering community, but it will have a large impact for a number of years.

As engineers and scientists learn more about material properties at the nanoscale, they will be better able to create new materials and find new uses for nanoparticles. The possibility even exists to build nano-sized devices and machines. Nanotechnology is an exciting application of materials engineering.

Materials Engineering in Action

Materials engineers use the principles and applications of materials engineering to select or create the most appropriate materials for an engineered solution. An engineer may be asked to select a material for a car bumper, a water bottle, the nose cone of a space shuttle, or the base of a hydroelectric dam. Each of these engineered solutions has different uses and different requirements for the materials. For example, the material for a water bottle does not need to withstand the same heat that the nose cone of a space shuttle does or the weight that is present at the base of a dam.

All engineers must consider several key elements as they select the most appropriate materials for their designs and solutions. Several of the elements include the material function, manufacturability, cost, and various forms of safety.

The first element considered is the material function. The engineer must consider how the material will be used in the design and how it is expected to perform. If the material needs to have a high tensile strength, they may choose from materials such as steel, titanium, fiberglass, carbon fiber, or even carbon nanotubes. However, the material may also need to be ductile, transparent, or conductive. These additional requirements would decrease the potential materials.

It is possible that engineers will not find a material that meets all of the functional requirements. In these cases, engineers must decide which of the functional requirements are most important. For example, they may decide that the high tensile strength is more important than high conductivity and then select an appropriate material. In other cases, it is possible to use several materials together either as a composite or in individual layers. Think of a raincoat that has several layers. The outer layer is designed to repel water and may be made from a type of plastic or a fabric made from plastic-coated fibers. This layer, however, may not keep you warm, so an additional layer of material, such as cotton or polyester, is added for warmth.

Manufacturability and costs are two other elements that the engineer must consider. These two elements are often related. ***Manufacturability*** is the ease at which the material can be transformed from raw material to a usable material. Cost is the monetary value of the material. There are a number of things that can impact the cost of a material, including availability and manufacturability. If the material is scarce or it is difficult to manufacture, it will cost more to use in a design. An example of how cost impacts material use can be found in the electrical wiring in your home. Silver is the best conductor of electricity, followed by copper and gold. Because the cost of the copper is much lower than silver or gold, it is used in home wiring. See **Figure 7-31**.

Figure 7-31.

Copper is used in home wiring because it is less expensive than silver or gold but is a good conductor.

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Aluminum has even been used in the past, when the price of copper was too expensive. The wide use of plastics in an enormous range of consumer products is due to the manufacturability and low cost of the material.

The final element of material selection is safety. Safety includes both the safety of the consumer and of the environment. Safety often becomes an issue years after materials have been used. For example, before the health concerns related to lead were known, it was widely used in paint. It was inexpensive to use and created rich colors in paint. However, today the health effects are understood and lead paint is not allowed to be used in all be a few industrial applications. Concerns are often raised and researched regarding materials and human safety. Today, some worry about the health effects of nanoparticles. That issue is being researched. The disposal of materials is also a concern of materials engineers. The disposal of plastics, electronic devices, and CFLs are current concerns, **Figure 7-32**. Many of these products have labels that describe how to dispose of them and many communities have specific methods for disposal of these products.

Figure 7-32. The disposal of electronic devices and plastics is of great concern.

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Summary

- Materials engineers design and create new materials and find new uses for existing materials.
- There is such a wide range of materials that materials engineers often need to specialize in one type of material.
- The principles of materials engineering include the types and properties of materials.
- Metals, ceramics, polymers, and composites are common categories of materials.
- Six categories of material properties are physical, mechanical, electrical and magnetic, chemical, thermal, and optical and acoustical.
- Materials are tested using destructive and nondestructive tests.
- An emerging area of materials engineering is nanotechnology. Nanotechnology deals with materials and devices at the nanoscale.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

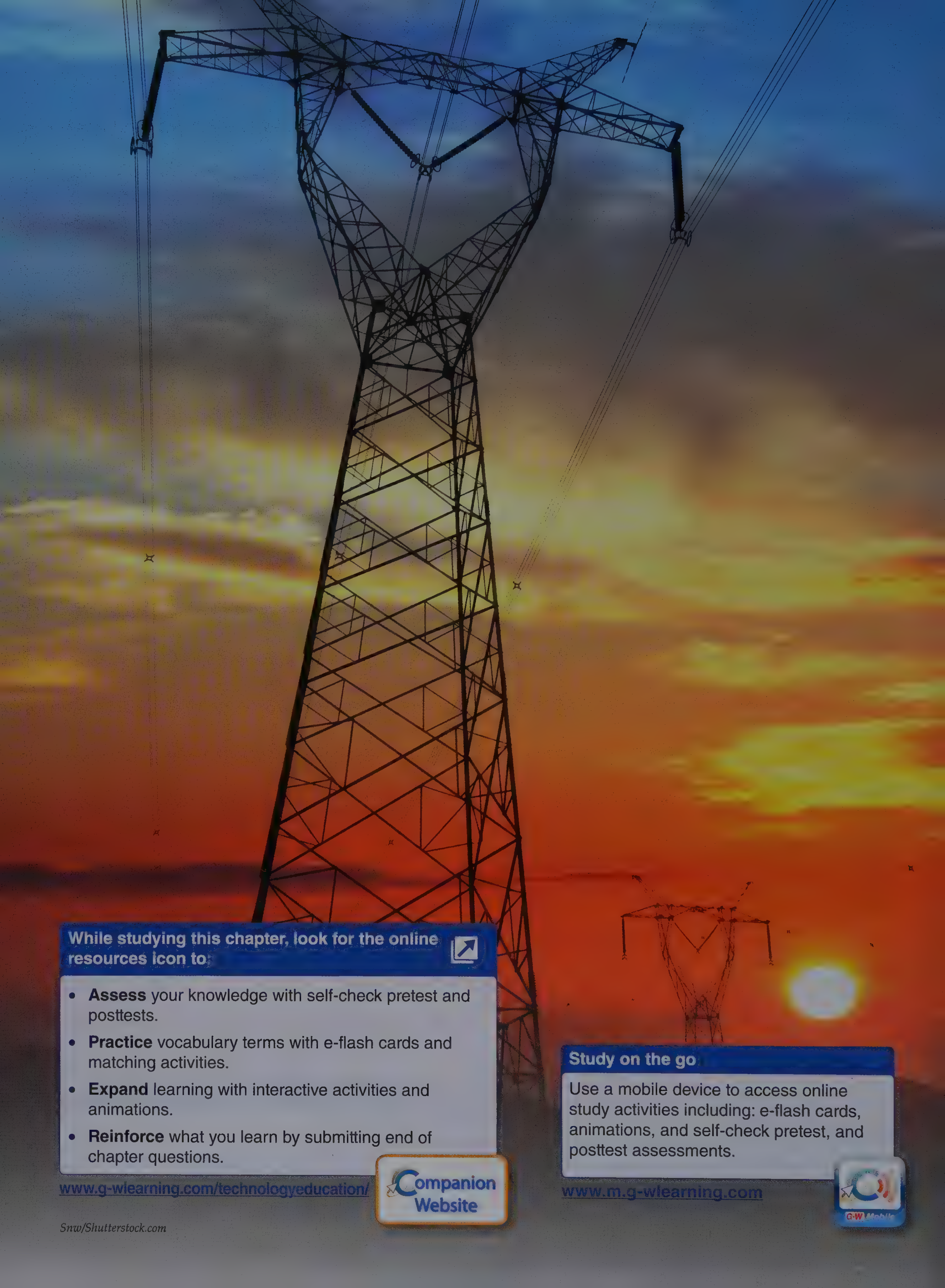
Assess *knowledge*

Test Your Knowledge Questions

Answer the following questions using the information provided in this chapter.

1. Define *materials engineering*.
2. The main function of the _____ organization is to develop material tests standards.
3. _____ are the most common element.
4. Brass is a(n) _____ made from copper and zinc.
5. *True or False?* Metals are an organic material.
6. _____ are nonmetallic solids made from inorganic material.
7. _____ are materials that are made up of a long chain of molecules that form a much larger molecule.
8. _____ have very strong chemical bonds and cannot be reshaped when heated.
9. Materials that are a combination of two or more materials are known as _____.
10. In fiberglass, the plastic is known as the _____ and the strands of glass are the _____.
11. Materials that are both insulators and conductors are known as _____.
12. Density is an example of a(n) _____ property.
13. Describe the difference between stress and strain.
14. If magnetic _____ is high, the material will allow magnetic flow.
15. Rusting is an example of _____.
16. R-values are used to express _____.
17. Radiography is an example of a(n) _____ test.
18. Define *nanotechnology*.
19. List two types of fullerenes that are used in nanotechnology.
20. List four elements that must be considered when selecting materials.

Reinforce *learning*



While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Chapter 8

Electrical Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- Define *electrical engineering*.
- Explain the secondary and college level education requirements for employment in the electrical engineering profession.
- Explain how electrons move on an atomic level.
- Describe the characteristics of voltage, current, resistance, and power.
- Explain Ohm's law and use it to solve for values in a circuit.
- Identify the operation and application of common electronic components such as resistors, switches, capacitors, diodes, and transistors.

Key Terms

alternating current (ac)
American Wire Gage (AWG) system
ammeter
atom
battery
capacitor
cell
circuit board
compact fluorescent lamp (CFL)
conductor
continuity tester
coulomb
current
diode
direct current (dc)
electrical engineering
electricity
electrode
electron
fluorescent lamp
gas discharge lamp
generator
hybrid car
incandescent lamp
Institute of Electrical and Electronics Engineers (IEEE)
insulator
integrated circuit (IC)
ion
law of conservation of energy
light-emitting diode (LED) lamp
motors
neutron
ohm (Ω)
ohmmeter
Ohm's law
oscilloscope
parallel circuits
polarity
power
primary cell
proton
resistance
resistor
schematic diagram
schematic symbol
secondary cell
semiconductor
sensor
series circuit
series-parallel combination circuit
solar cell
solderless breadboard
static electricity
switch
transistor
troubleshoot
valence shell
variable resistor
volt
voltage
voltmeter
volt-ohm-milliammeter (VOM)
watt
Watt's law
zener diode

Practice *vocabulary*

Have you ever wondered who designs and builds things like power plants, space shuttle electronics, or your favorite electronic gadget? You can be sure that electrical engineers were involved in every step along the way. ***Electrical engineering*** is the design and construction of electrical and electronic components and devices. Electrical engineers design, test, develop, and build products like these every day. About 21% of all engineers, or roughly 153,000 people, are electrical engineers. See **Figure 8-1**.

In telecommunications, electrical engineers are responsible for designing and overseeing the construction and maintenance of the systems and networks through which customers receive voice and data services. They deal with copper telephone equipment, fiber optics, electronic switching systems, radio and television systems, and satellite systems.

Professional Aspects

The requirement for an entry-level electrical engineer is a bachelor's degree in electrical engineering. For higher-level positions, master's degrees or doctorate degrees are usually required. To earn a degree in electrical engineering, courses must be taken in electricity, electronics, chemistry, biology, physics, and higher-level math and statistics. In order to be accepted into an engineering program, students need high grades in advanced high school math and science classes.

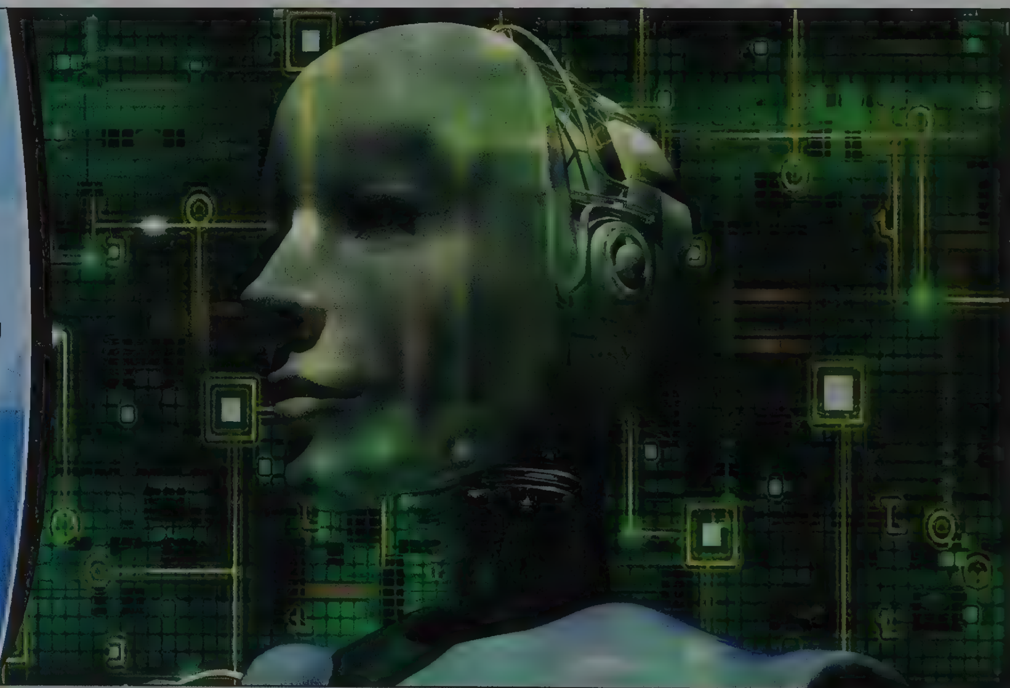
Electrical technicians are commonly responsible for installation and maintenance of electrical equipment and devices. Becoming an electrical technician usually requires a two-year associate's degree.

The broadest professional society for electrical engineers is the ***Institute of Electrical and Electronics Engineers (IEEE)***. The acronym is pronounced *I triple E*. IEEE comprises over 375,000 members in more than 160 countries. The IEEE is dedicated to advancing technological innovation and excellence through their publications, conferences, standards, and activities. See **Figure 8-2**.

Electrical Engineering Principles

There are a number of basic electrical concepts that are fundamental to the job of electrical engineer. Electrical engineers must know what electricity is,

Figure 8-1.
Electrical engineers are designing new and exciting products every day.



NesaCera/Shutterstock.com

Figure 8-2.
Several electrical engineers are a part of the Institute of Electrical and Electronics Engineers.

Stephen Coburn/Shutterstock.com

how it is created, how it is transmitted and controlled, how it is changed into a form of energy that meets human needs and wants, and, most importantly, how to deal with electricity in a safe manner.

Electricity on the Atomic Level

To understand *electricity*, or the movement of electrons, it is important to first understand the atom. All matter is made up of microscopic building blocks called *atoms*, which are like microscopic models of our solar system. The planets in our solar system orbit around the sun. In much the same way, atoms are made up of electrons, protons, and neutrons. Negatively charged subatomic particles called *electrons* orbit around a nucleus, which is made up of positively charged *protons* and electrically neutral *neutrons*. **Figure 8-3** shows a diagram of an atom.

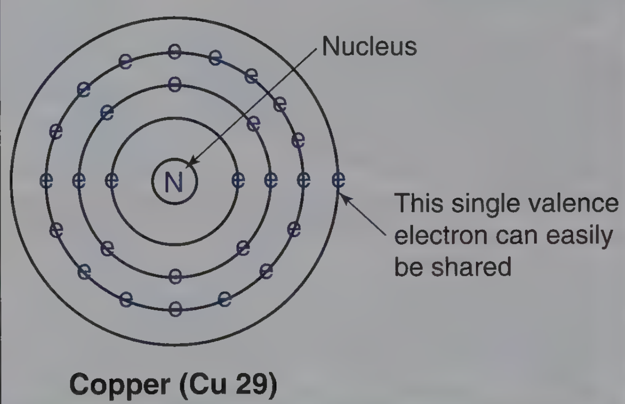


Figure 8-3.
This atom shows protons, neutrons, and electrons.

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Most atoms have an equal number of protons and electrons, which makes them electrically neutral. Under normal circumstances these atoms are stable. When an outside force like energy is introduced to an atom, it becomes excited. If the atom becomes excited enough, it can lose electrons from its outer ring, which is called the *valence shell*. *Ions* are electrically charged atoms. Atoms that gain an electron take on a negative charge and become negative ions. Atoms that lose an electron take on a positive charge and become positive ions. The fewer the electrons in the valence shell, the more easily an atom can share electrons. The concept of electrons moving from one atom to another is critical to understanding electricity.

Static Electricity

Static electricity is the excess of charge on the surface of an object. Have you ever dragged your feet on the carpet or gone down a plastic slide and then gotten a bit of a shock when you touch something metal, such as a doorknob? If so, you have seen static electricity in action. As you rub against the carpet or slide, you develop a charge. The charge is neutralized when you touch a material capable of conducting electricity.

Static electricity has many industrial applications. One of the most popular applications is the electrostatic precipitator, which can be used to remove particles from the air. See **Figure 8-4**. Particles are charged on their way in, and the collection plates are given an opposite charge. The particles then stick to the plates.

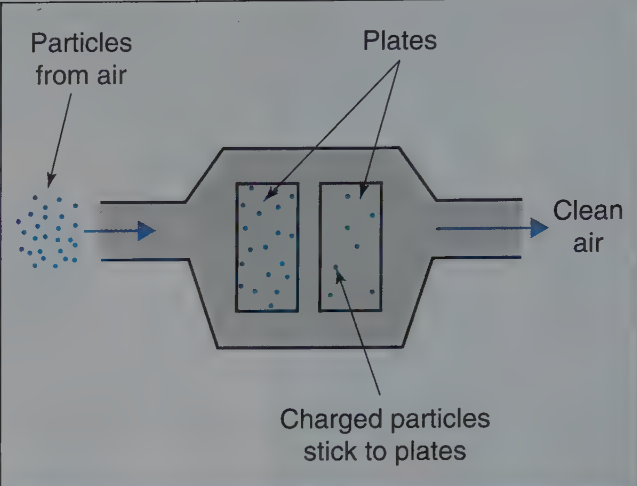

Figure 8-4.
This schematic of an electrostatic precipitator shows how particles are filtered from the air using static electricity.

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Electricity through a Conductor

Electricity usually flows through a solid piece of material called a ***conductor***. Copper, in the form of copper wire, is the most commonly used conductor. There are two theories of electrical current flow: conventional current flow theory and electron flow theory. The conventional current flow theory states that electrical current flows from negative to positive. Electron flow theory states that electrons flow from negative to positive because the negatively charged electrons are attracted to the positively charged protons. Individual electrons in the conductor move almost as slowly as the minute hand on a clock. The effect of electricity (rather than actual electricity) moves at the speed of light, which is roughly 186,000 miles per second. It is the effect of electricity flowing because the copper wire is full of electrons. When one electron is added to one end, it pushes on all of the electrons in the wire until one pops out the other end. Each electron only moves a tiny bit inside the wire, but the effect is as if an electron flowed all the way through from one end to the other. Think of a long tube full of balls. If you push a ball in one end of the tube, a ball immediately comes out of the other end. Your ball does not travel the entire length of the tube. Each ball moves a little bit, which makes it seem like your ball instantly comes out the other end. See **Figure 8-5**.

Sources of Electricity

You may have wondered where the electricity comes from to power your lights at night or to operate the *International Space Station*. Sources of electricity include magnetism, chemical action, and solar cells. In each case some form of energy is converted into electrical energy. The ***law of conservation of energy*** states that energy cannot be created or destroyed. It can only be converted from one form to another.

Magnetism

Most electricity is produced using electric generators. ***Generators*** produce electricity by changing mechanical energy to electrical energy. When a magnet passes by a wire, a small amount of voltage is induced in that wire. Voltage is the electrical force that causes electrons to move. The action of producing voltage in a wire this way is called *induction*. As a generator turns, a conductor is passed across invisible lines of magnetic force that surround magnets called magnetic lines of flux, and a current is induced in the conductor.

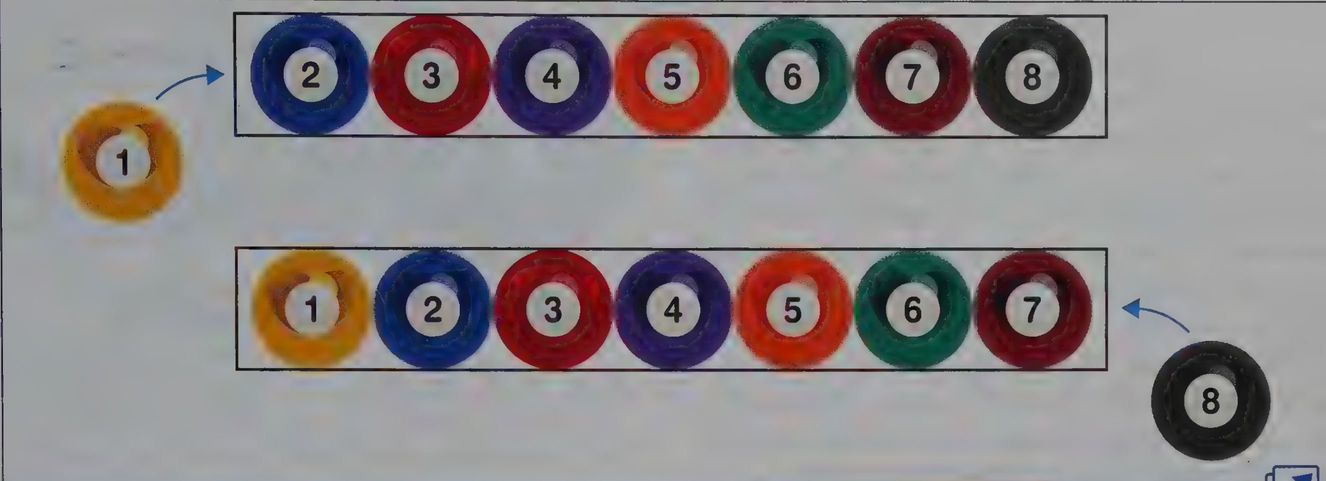

Figure 8-5. Expand learning

When a ball is pushed into one end, a ball comes out the other end immediately. Each ball in the tube moved a short distance, but the effect was that one ball moved very quickly.

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See **Figure 8-6**. In coal, nuclear, and natural gas power plants, tremendous amounts of steam are generated. This steam is used to turn massive turbines, creating rotary motion that spins a generator. In hydroelectric dams, falling water is used to turn turbines. These turbines then turn generators. In wind farms, turbine blades are turned by the wind to create rotary motion for the generator.

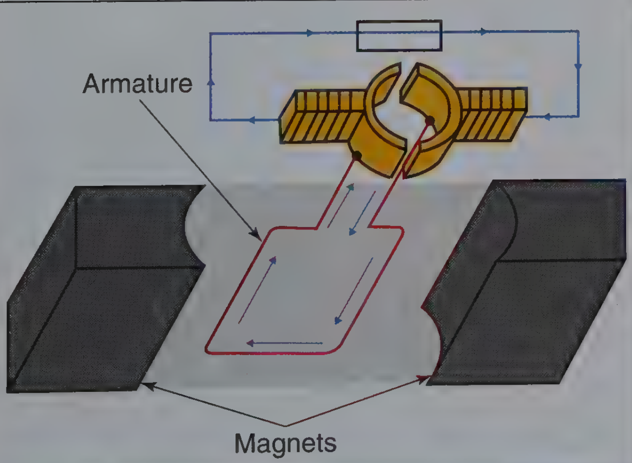

Figure 8-6.

This simple generator produces electricity by changing mechanical engery to electrical energy.

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Science

Magnetism

Magnets are important in the area of electrical engineering because they are used to generate electricity. A magnet is usually made of iron, steel, or a mixture of metals. A magnet contains polarities. Polarity describes the direction of a magnetic field. The magnetic field is strongest at a magnet's poles, each in the direction opposite of the other. A magnet has two poles. The Earth is considered a magnet with two poles: north and south.

Every magnet has two poles. If you cut a magnet in half, each piece would then have two poles. Like poles repel each other, while opposite poles attract. For example, the north pole of one magnet will attract the south pole of another magnet. However, the north poles of two magnets will push away from each other.

Every magnet has a magnetic field created by its poles. A stronger magnetic field is created between two magnets with opposite poles. The field surrounds the magnets and pulls them closer together. The magnetic fields of two magnets with similar poles are different. Because the magnets repel each other, their magnetic fields stay as they are.

Chemical Action

Cells create electrical energy using a chemical action. A ***battery*** is an electrical connection of two or more cells. An ***electrode*** is a solid conductor through which electricity enters or leaves a medium. When two electrodes made of different materials are placed in an electrolyte, electrons gather on the negative terminal and a voltage builds up between the electrodes. The electrolyte acts chemically on the electrodes and conducts electrons between the electrodes. Disposable batteries are called ***primary cells*** and batteries that can be recharged are called ***secondary cells***.

Making a cell can be as simple as soaking a paper towel in salt water and placing it between a nickel and a penny. A very small voltage can be read between the nickel and penny. **Figure 8-7** shows a very simple cell that you can make.

Solar Cells

Solar cells use light to create electricity. Inside a solar cell, a layer of positive semiconductor material is sandwiched together with a layer of negative semiconductor material. Semiconductors, such as silicon, have conductive properties between those of conductors and insulators. When light shines on the cell, some of the light energy is absorbed.

History

Electrical Engineering in History

Many people have contributed to the development of batteries throughout history, but one man's contribution stands above the rest. An Italian physicist named Alessandro Volta is credited with inventing the battery. A colleague of Volta, Luigi Galvani, discovered that a dead frog's leg would twitch when the nerves were touched with unlike metals. He believed that the animal tissue contained a cell potential, which he called animal electricity.

Alessandro Volta expanded on Galvani's discovery by demonstrating in 1791 that electrical current can be produced by layering unlike metals (copper and zinc) with cardboard or cloth soaked in salt water. He later piled up numerous layers of unlike metals (like cells wired in series) to create more current. This is called the *voltaic pile*, and it was the first battery capable of providing sustained electrical current.

Volta discovered that he could measure the difference in charge or electromotive force from the top of the stack to the bottom. The measurement unit *volt* is named for him.

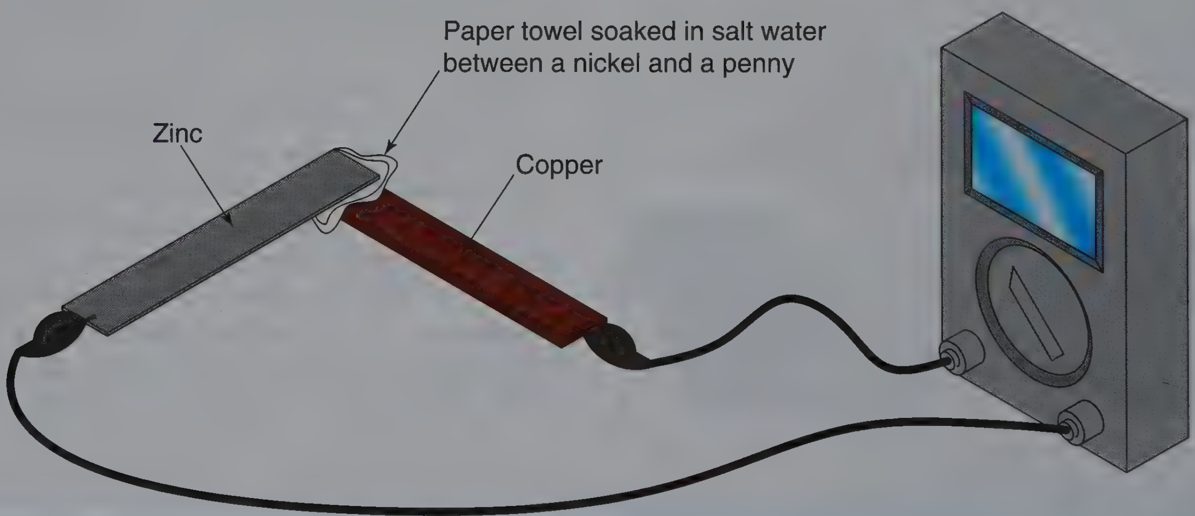

Figure 8-7.

This is a basic cell. Unlike metals are separated by a paper towel soaked in salt water.

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This energy knocks electrons loose, and they begin to flow in the form of electrical current. Many small cells can be connected to power devices like calculators, satellites, and even whole houses. See **Figure 8-8**.

Characteristics and Measurements

Once electricity is generated, it has certain characteristics that electrical engineers use in a number of different ways. It is important for electrical engineers to understand these characteristics and how to measure them.

Figure 8-8.

Solar cells can be used to power several different types of devices, such as this navigational buoy.

Spectruminfo/Shutterstock.com

Voltage

Voltage is the amount of pressure causing the flow of electrons, which is expressed as electromotive force (EMF). Voltage is also known as potential difference because it describes the difference in charge from one place to the other. A higher voltage will cause more electrons to flow. The letter *E* is often used as an abbreviation for voltage and stands for electromotive force. Voltage is measured in ***volts***. The abbreviation for volts is the letter *V*. The typical wall outlets in a house provide 120 V, while a battery used to power a flashlight might provide 1.5 V.

Current

Current is a measure of the flow of electrons per unit time. To understand current, you must first understand ***coulombs***, which is a measure of the amount of electricity. One coulomb is equal to 6.24×10^{18} electrons. The term *amperage* is also used to describe current.

When discussing the flow of electrons, it is important to include time. As an example, let's say 100 students walked down the hall in front of your classroom. That doesn't mean much to you unless you know the time frame. Did it take all day for 100 students to pass by? Would it mean more if it were 100 students in two minutes?

One ampere, or amp, is the measurement of one coulomb of charge passing a point in one second. The letter *I* is used as an abbreviation for current because it stands for intensity. Current is measured in amps. The letter *A* is used as an abbreviation for amps. For example, a common 100-watt lightbulb draws about 0.83 amps.

Polarity refers to the positive or negative condition at the power supply terminal. Sometimes polarity is constant and current flows in only one direction. This is called ***direct current (dc)***. Sometimes the polarity changes back and forth from positive to negative, causing current to go back and forth. This is called ***alternating current (ac)***. Batteries supply direct current. A battery-operated flashlight uses dc. The wall outlets in your school provide ac. **Figure 8-9** shows the difference between ac and dc.

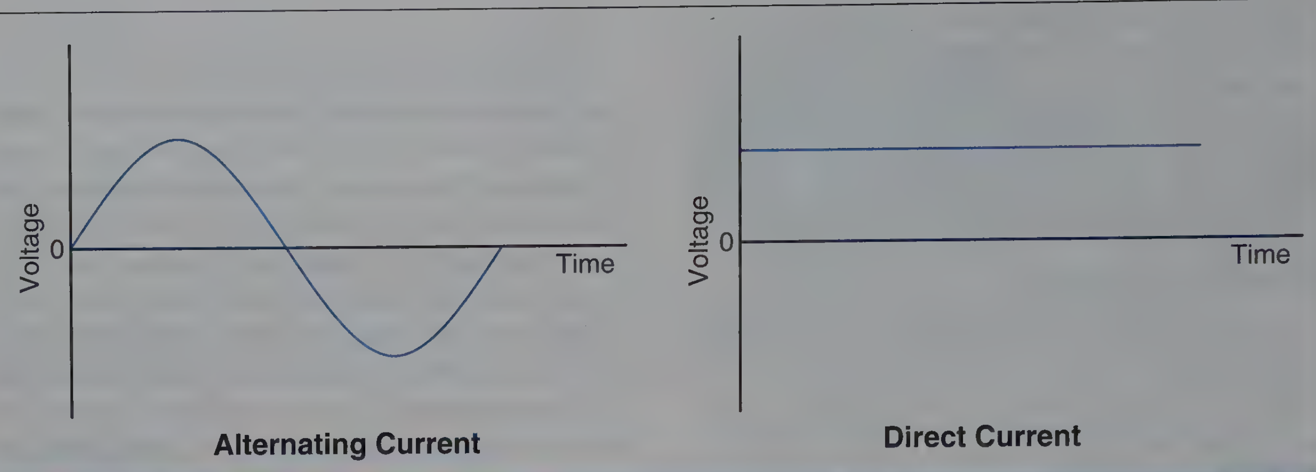

Figure 8-9.

The ac wave crosses the zero line and changes polarity. The dc wave does not cross the zero line.

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Resistance

Resistance is the opposition to current flow. ***Resistors*** are used to limit current flow and divide voltage. All conductors, components, and circuits have some level of resistance. Resistance is measured in ***ohms***. The Greek symbol for omega (Ω) is used to represent ohms.

Materials with very little resistance (allow current to flow freely) are conductors. Copper, aluminum, gold, and silver are examples of good conductors. Materials with a very high resistance that do not allow current to flow are called ***insulators***. Plastic, glass, rubber, and paper are examples of good insulators.

A standard kitchen faucet can help you understand the relationship between current, voltage, and resistance. Think of the water pressure as voltage, the amount of water flowing as current, and the faucet handle as providing resistance. In this example, the water pressure (voltage) remains constant as it is supplied from the water system. If the water is turned on as far as possible, there is very little resistance from the faucet and, therefore, very high flow (current). By slowly turning the faucet handle, resistance is increased and flow (current) is decreased. This example shows that if voltage is held constant, current and resistance are inversely proportional. If resistance increases, current decreases. If resistance decreases, current increases.

Power

Power can be defined as the rate at which work is done or the amount of work done based on a period of time. Electrical power can be defined as the product of voltage and current. The ***watt*** is the unit of electrical power. It is named for the inventor of the steam engine, James Watt. One watt is the measure of one volt moving one coulomb of electricity in one second.

Laws

Ohm's law is the relationship between resistance, current, and voltage in electrical circuits. This law is one of the most important concepts to master in the field of electrical engineering because it will be used more than any other. Ohm's law was named for a nineteenth century German physicist named Georg Ohm. He discovered that if he kept resistance constant and varied voltage, dividing the voltage by the current always equaled the resistance. This formula can be used to solve for any of the three variables:

$$R = E / I$$
$$I = E / R$$
$$E = I \times R$$

For example, let's say you want to calculate the resistance of a flashlight bulb. You know that your batteries are providing 3 V and you are drawing 0.1 A (or 100 milliamps) of current flow.

Math

Scientific Notation

It is very common to encounter extremely large and small numbers when working with or studying electricity and electronics. Sometimes numbers are too large or small to be conveniently written. They can be represented using scientific notation. The base number in scientific notation is a number from 1 to 9 and is multiplied by a power of ten.

For example, 7×10^3 (seven times ten to the third power) is $7 \times 10 \times 10 \times 10 = 7{,}000$. The *3* is an exponent. Exponents show how many times to use the number in multiplication. Positive exponents are used for numbers larger than the base number, and negative exponents are used for numbers that are smaller than the base number.

For example, imagine you want to represent 5 Megawatts using scientific notation. The metric prefix Mega- refers to million. Therefore, you are trying to show 5,000,000 watts. That can be shown as $5 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$. Using scientific notation, it is 5×10^6 watts.

The metric prefix milli- is used to show thousandths of a base number. For example, 7 milliamperes is 7 thousandths of 1 ampere, or 0.007 amperes. Using scientific notation, this is shown as 7×10^{-3}. The exponent is –3 because the decimal place moves to the right 3 places from 7 to 0.007.

See **Figure A** showing common metric prefixes and the symbols, decimal value, and value in scientific notation.

Write the following numbers using scientific notation, converting units where necessary.

1. 8,730,000,000 watts
2. 6,270 nanovolts
3. 0.00047 amperes
4. 4,383,000 ohms
5. 2,000 volts
6. 3.2 kilohms

Prefix	Symbol	Value	Decimal
Giga-	G	10^9	1,000,000,000
Mega-	M	10^6	1,000,000
Kilo-	k	10^3	1,000
Milli-	m	10^{-3}	0.01
Micro-	μ	10^{-6}	0.000001
Nano-	n	10^{-9}	0.000000001
Pico-	p	10^{-12}	0.000000000001

Figure A.

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Use the following formula:

$$R = E / I$$
$$= 3\ V / 0.1\ A$$
$$= 30\ \Omega \text{ of resistance}$$

The handy reminder in **Figure 8-10** can be used to find all three formulas. If you place your finger over the quantity you are looking for, you will see the necessary formula. For instance, cover the *R* with your finger and you will see *E* / *I*.

Watt's law states that power equals effort multiplied by rate. This can be expressed using the following formula:

$$P = I \times E$$

Using this formula, you can find any one of the three values when two are known. Let's say you wanted to know how much current was flowing through a 100-watt incandescent lightbulb in your home. You know that the supply voltage is 120 V and the bulb is rated for 100 W.

You would use the following formula:

$$I = P / E$$
$$= 100\ W / 120\ V$$
$$= 0.84\ A \text{ of current flowing through the lightbulb}$$

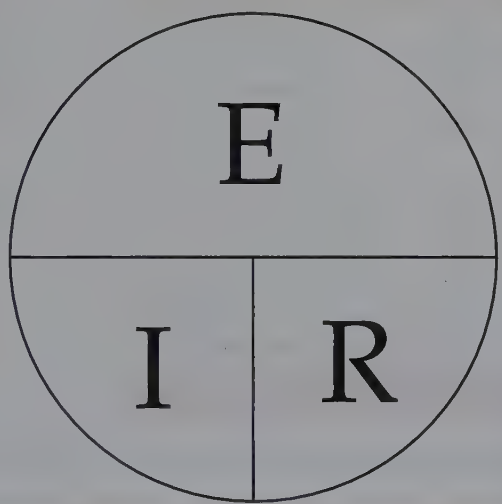

Figure 8-10.

This diagram can help you remember the three formulas related to Ohm's law.

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Your electric bill at home is calculated in kilowatt-hours, or thousands of watt-hours. If you take the wattage used times the number of hours it was used, you can find the watt-hours. Let's say you turn on a 100-watt lightbulb for ten hours.

100 watts × 10 hours = 1,000 watt-hours = 1 kilowatt-hour

As an example, if you are being charged 15 cents per kilowatt-hour by your local power company, it costs 15 cents to operate that 100-watt lightbulb for 10 hours.

Applications

Electrical engineers use their knowledge of the characteristics and laws of electricity to design applications for its use. The applications utilize circuits and electrical components.

Basic Circuits

The most basic circuit consists of a power source, a load (device that uses the electricity), and conductors to connect them. Electrical circuits can be designed in three ways. They are series, parallel, and series-parallel. Electrical engineers must understand these circuits in order to understand, design, build, and troubleshoot electrical devices. Each circuit has unique benefits and drawbacks for given situations.

Series Circuits

Series circuits have only one path for current to flow from the power source through the circuit and back to the power source. Current leaves the power source, flows through all loads in the circuit, and goes back to the power source.

Holiday light strings are a good example of series circuits. The current in these lights runs through each individual light and back to the power source. If one light burns out, every light in the string turns off due to that one open in the circuit. **Figure 8-11** shows a schematic drawing of lights wired in series.

Voltage in a series circuit is equal to the sum of the voltage drop across each load in the circuit. The voltage drop across each load varies

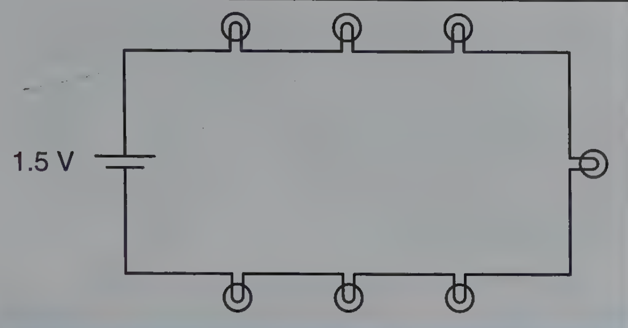

Figure 8-11.

This is a typical series lighting circuit. Current must pass through all seven incandescent lamps in this example.

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in proportion to its resistance, but the sum of all drops equals the applied voltage. Use a string of 60 holiday lights wired in series as an example. They would be plugged into a common 120 V household electric outlet. To find the voltage drop across each light, divide 120 V by 60 lights. There is a voltage drop of 2 V across each light.

This can be expressed as:

$$E_t = E_1 + E_2 + E_3 + \ldots + E_N$$

Total resistance in a series circuit is equal to the sum of the resistance of each individual load. For example, picture three resistors wired in series. Their values are 10 Ω, 20 Ω, and 30 Ω. The total resistance in the circuit is the sum of all resistances, or 60 Ω. This can be expressed as:

$$R_t = R_1 + R_2 + R_3 + \ldots + R_N$$

Current is constant throughout a series circuit. Think of water flowing through a garden hose. Whatever flow goes into one end of the hose will flow through and come out the other end. This is the same in electricity. In the previous example, the three resistors have a total resistance of 60 Ω. If they are connected to a 120 V power source, there will be 2 A (120 V / 60 Ω = 2 A) of current flowing at every single point in the circuit. No matter where the current is tested, it would read 2 A. This can be expressed as:

$$I_t = I_1 = I_2 = I_3 = \ldots = I_N$$

Parallel Circuits

Parallel circuits have more than one load and have multiple paths for current flow. Each path is a branch and contains one load. Current is divided between the branches in proportion to the resistance of the load in each branch. In other words, the branch with the lowest resistance will have the highest current flow. The voltage across the load in each branch is equal to the source voltage.

Many modern holiday lights are wired in parallel. Each light is wired into its own branch in the circuit. If one light burns out, only that one light turns off and the rest stay lit. **Figure 8-12** shows a typical parallel lighting circuit.

Voltage in a parallel circuit is the same across each load as it is at the source. All loads get the total source voltage. Think of your home as an example. Numerous receptacles and lights might be on the same circuit, but they all get 120 V. Voltage in a parallel circuit can be expressed as:

$$E_t = E_{R_1} = E_{R_2} = E_{R_3} = \ldots = E_{R_N}$$

In a parallel circuit, the sum of all branch currents equals the total current in the circuit. In other words, to find the total current in a circuit, add all of the branch currents together. Current in a parallel circuit can be expressed as:

$$I_t = I_{R_1} + I_{R_2} + I_{R_3} + \ldots + I_{R_N}$$

Resistance in a parallel circuit is a bit more complicated. The total resistance in a parallel circuit is always lower than the lowest branch resistance.

Figure 8-12.

This is an example of a typical parallel lighting circuit.

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Adding more branches to a parallel circuit causes the total resistance to decrease. Resistance in a parallel circuit can be expressed as:

$$R_t = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_N}}$$

Series-Parallel Combination Circuits

Series-parallel combination circuits are not simply series or parallel. They are a combination of both types of circuits. Therefore, the rules and formulas for solving a series or parallel circuit cannot be used. In order to study a series-parallel circuit, the parallel parts must be broken down and studied as if they were series elements. **Figure 8-13** shows a series-parallel circuit with three lights where the first light is in series and the other two lights are in parallel. The light in series would be much brighter because it receives roughly twice the current of each of the other two.

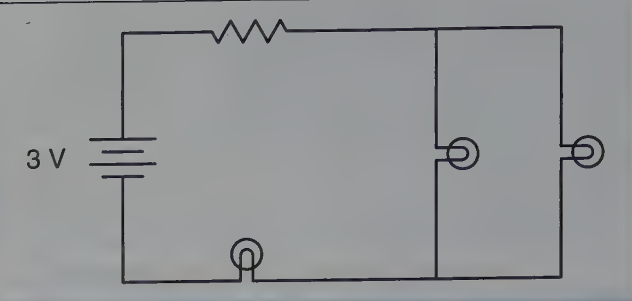

Figure 8-13.

This schematic shows a series-parallel lighting circuit.

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Circuit Components

Electrical engineers must fully understand each component that can be used in a circuit. Electrical engineers often design, build, and troubleshoot electrical circuits. They must know how each component of the circuit works so they can select the best parts to solve a given design problem or troubleshoot a circuit that is not working properly.

Conductors

Conductors provide a path for current to flow to the parts that will control and use it. Materials with very low resistance are conductors. They easily share electrons from one atom to the next when a charge is applied. Copper is the most common conductor. Aluminum is not quite as good as copper, but is lighter and less expensive. Aluminum is often used in thick service entrance cables that bring electricity into houses. Silver and gold are better conductors than copper and aluminum, but are only used in very specific applications due to their cost.

Conductors come in a wide variety of configurations. They can be solid wire, stranded wire, ribbon, and bar shapes based on their intended use. For example, solid copper wire is commonly used in residential wiring because it does not need to move once it is installed. If a solid conductor is bent back and forth too many times, it will break like a paper clip that is bent repeatedly. Stranded copper wire is used in extension cords because it bends easily and will not break over time.

Conductors are sized based on their cross-sectional area. The size of round conductors is determined using the ***American Wire Gage (AWG) system***. In the AWG system, smaller numbers represent larger wire. For instance, 12-gage wire is larger than 30-gage wire. 14-gage wire is commonly used in houses for general lighting and receptacle circuits. **Figure 8-14** shows common wire types.

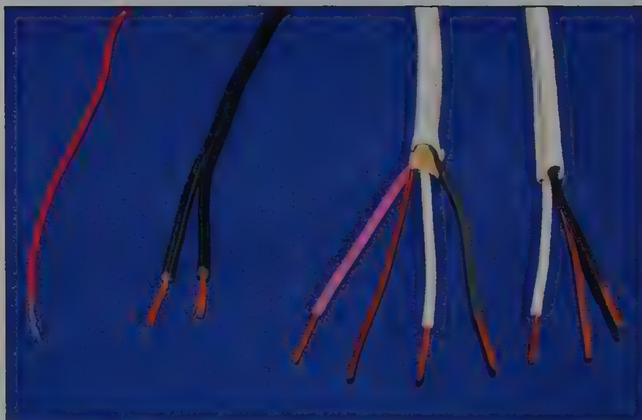

Figure 8-14.

Common solid, stranded, one-conductor, two-conductor, and three-conductor wire types are shown.

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Design

Schematics

When drawing electrical circuitry, it is much easier to use simple symbols for parts than it is to draw pictures. These basic symbols are called ***schematic symbols***. A ***schematic diagram*** is a basic sketch of circuitry showing schematic symbols for parts and lines to represent conductors. Using a schematic diagram, electrical engineers can build or troubleshoot complex circuitry. Electrical engineers also use schematic diagrams in the circuit design phase. **Figure A** shows schematic symbols for common electronic components.

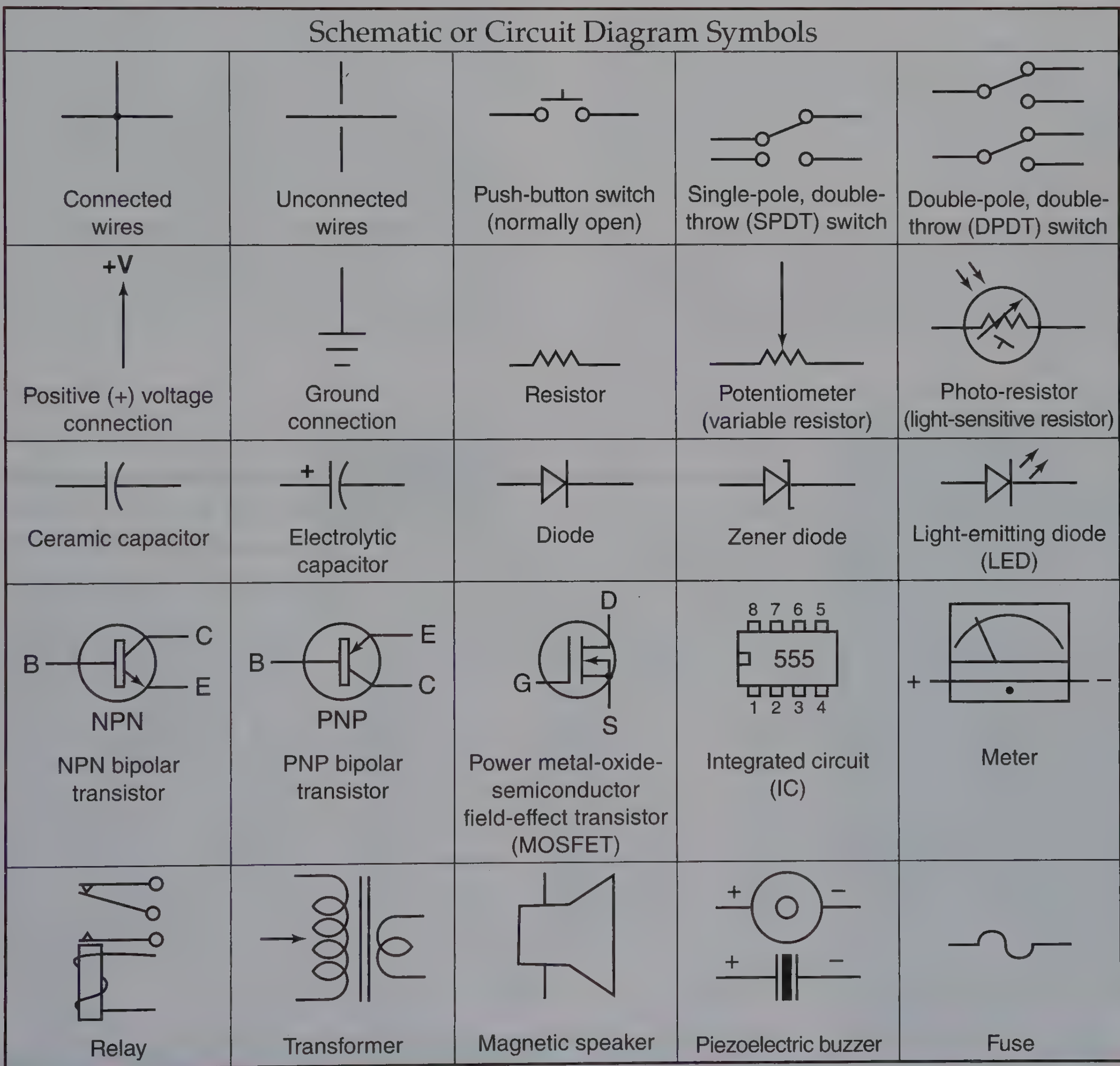

Figure A.

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Control Components

Control devices direct and/or limit current flow so a circuit meets its desired function. For example, insulators keep current in the conductor and protect against shorts, and resistors limit current flow to protect sensitive components.

Insulators

Materials with extremely high resistance that do not conduct electricity under normal circumstances are insulators. The most commonly used insulators are plastic, glass, paper, rubber, and mica. Insulators are used to keep electricity confined to the desired circuit path and away from people and other parts of the circuit. A short circuit can be defined as an undesired path to ground. In a short circuit, electricity is able to neutralize its charge without having to flow through the load. Without the resistance provided by the load, current increases dramatically, which can cause a fire or other damage.

Resistors

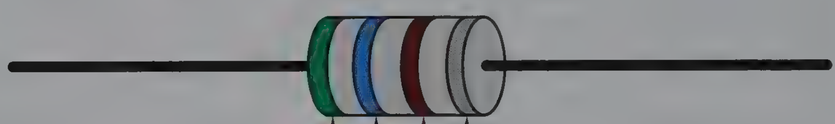
The resistor is one of the most common and reliable electrical components. Resistors are used to limit current flow and divide voltage in a circuit. Resistors come in a variety of sizes, shapes, and configurations. Most are made from carbon. Resistors are available in values ranging from less than one ohm to many millions of ohms.

A system of color-coding resistors with their values was developed because it is not always possible to print values on very small resistors. Resistors typically have three or four (sometimes five) color bands. The first two colors represent digits. The third band is the multiplier and tells what power of ten the digits should be multiplied by. The fourth band is the tolerance, which indicates the accuracy of the resistor value. If there is no fourth band, a twenty percent tolerance is assumed. On a five-band resistor, the first three are digits, the fourth is the multiplier, and the fifth is the tolerance.

Look at the resistor color code chart in **Figure 8-15**. Think of a resistor whose color bands from left to right are green, blue, brown, silver.

The first two colors represent digits. The digit for green is 5 and the digit for blue is 6. Place these two numbers next to each other and you have 56. The third band is the multiplier and in this case it is brown, which has a value of 10.

So now we have $56 \times 10 = 560$. This is referred to as a 560 Ω resistor.



First Band 1st Digit	
Color	Digit
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Second Band 2nd Digit	
Color	Digit
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

Third Band Multiplier	
Color	Multiplier
Black	1
Brown	10
Red	100
Orange	1,000
Yellow	10,000
Green	100,000
Blue	1,000,000
Silver	0.01
Gold	0.1

Fourth Band* Resistance Tolerance	
Color	Tolerance
Silver	± 10%
Gold	± 5%
*No Band	± 20%

green 5 | blue 6 | brown 10 | silver ± 10%

560 Ω

± 560 Ω
504 Ω–616 Ω

Figure 8-15. This resistor color code chart shows the numerical values and tolerances for resistor color stripes.

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The fourth band is the tolerance and in this case it is silver, which has a value of 10%. This means that the measured value of this resistor could be 10% above or below 560 Ω.

In order to find 10% of 560, do the following:

$560 \times 0.1 = 56$

$560 - 56 = 504$

$560 + 56 = 616$

So the measured value of this 560 Ω resistor with a 10% tolerance could be anywhere between 504 Ω and 616 Ω.

Variable Resistors

At times, such as in dimmer switches and fan speed switches, it is important to vary the amount of resistance. In these situations, resistors whose resistance can be changed, known as ***variable resistors***, are used. Variable resistors have two terminals and a wiper, which is a knob or a sliding switch. As the wiper moves along a piece of resistive material, usually carbon, the amount of resistive material between the terminals changes, and so does the resistance. Note the arrow on the schematic for variable resistors. An arrow on a schematic indicates that its value is variable. **Figure 8-16** shows common variable resistors.

Figure 8-16.

These are common variable resistors.

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Switches

Switches are used to control the flow of electricity in a circuit. They open and close (turn off and on) the circuit or direct the flow of electricity into a different circuit. Switches come in a wide variety of configurations to meet the specific needs of each application. Switches are characterized by the type of switch, the number of poles, and the number of throws. The number of poles indicates the number of paths for current flow into the switch. The number of throws indicates the number of paths leaving the switch. A single-pole single-throw (SPST) switch has one path for current flowing in and one path flowing out. This switch can only turn the current on or off to one circuit. For example, a switch on a lamp is usually a SPST switch. A single-pole double-throw (SPDT) switch can direct the current in one direction or the other. A common use for the SPDT switch is a lighting circuit where a light can be turned on or off from two different locations. In **Figure 8-17**, a light can be turned on or off from each of two SPDT switches.

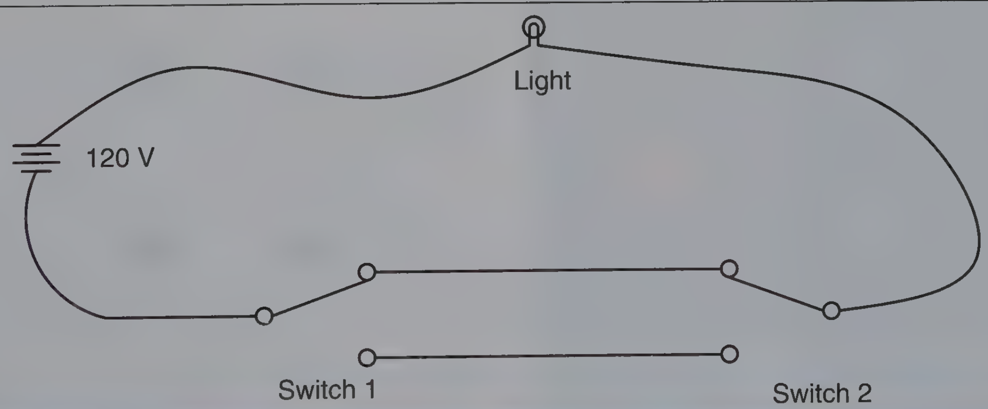

Figure 8-17.

In this example, a light can be controlled from either of the two single-pole double-throw switches.

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Diodes

Standard ***diodes*** are designed to allow current flow in only one direction. They can be used as rectifiers to change alternating current to direct current. Diodes have two electrodes called the *anode* and the *cathode*. The anode is made of a positive (P-type) semiconductor material and the cathode is made of a negative (N-type) semiconductor material. For the diode to allow current to flow, the correct polarity must be applied. Polarity is the condition of being positive or negative with respect to ground. The negative power supply terminal must be connected to the cathode (–) and the positive terminal must be connected to the anode (+). This is called *forward bias*. Current will flow in forward bias. If the negative power supply terminal were connected to the anode and the positive to the cathode, a reverse bias condition would exist. Current cannot flow in reverse bias. See diodes being used in a bridge rectifier in **Figure 8-18**. Bridge rectifiers change ac to dc.

Zener Diodes

Zener diodes conduct electricity in reverse bias. They block current until the voltage reaches a certain level. Once this level is reached, zener diodes conduct and help to keep the voltage at a constant level. Because of this characteristic, they are often used as voltage regulators, which help to smooth out variations in voltage.

Transistors

Transistors can be used as solid-state switches and as amplifiers. They are called *solid-state switches* because they perform a switching function with no moving parts. Bipolar transistors have three junction points: emitter, base, and collector. Current flowing between the emitter and collector can be controlled by a current delivered to the base. Transistors can also be used as amplifiers. Amplifiers increase the power of a signal, most commonly an audio signal. A small amount of current applied to the base can create a gain in collector/emitter current. **Figure 8-19** shows a PNP and an NPN transistor.

Capacitors

Capacitors have the ability to store and discharge electricity very quickly. They can store much less electricity by volume than a battery, but they can discharge and recharge much more quickly. Capacitors can smooth out (filter) variations in voltage and can block continuous dc flow while allowing pulses to pass. Capacitors can smooth out variations in voltage by absorbing the spikes and filling in the valleys. For example, the internal workings of computers require dc, but wall outlets supply ac. Inside of computers, ac is rectified, or changed, to dc. This dc voltage can vary a great deal. Capacitors are used to smooth out or filter the voltage.

Figure 8-18.
Schematic of a bridge rectifier, which converts ac to dc.

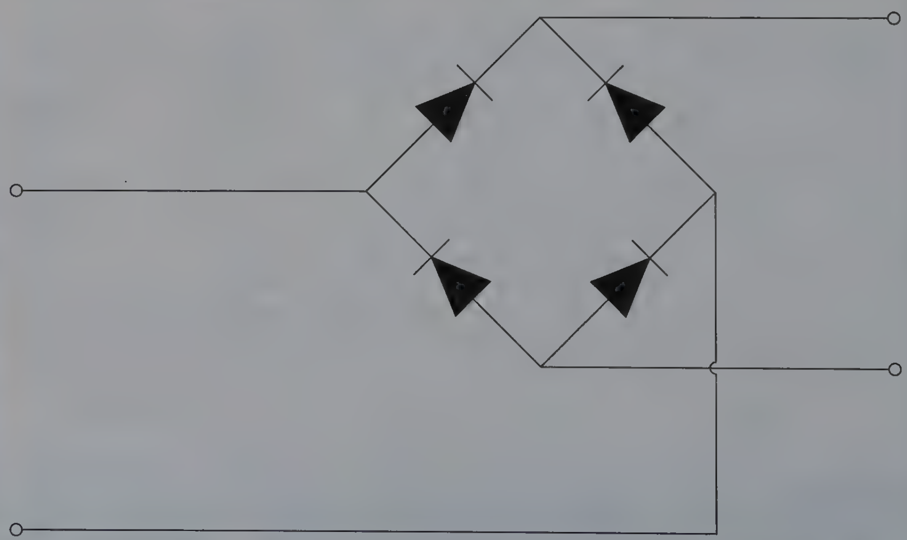

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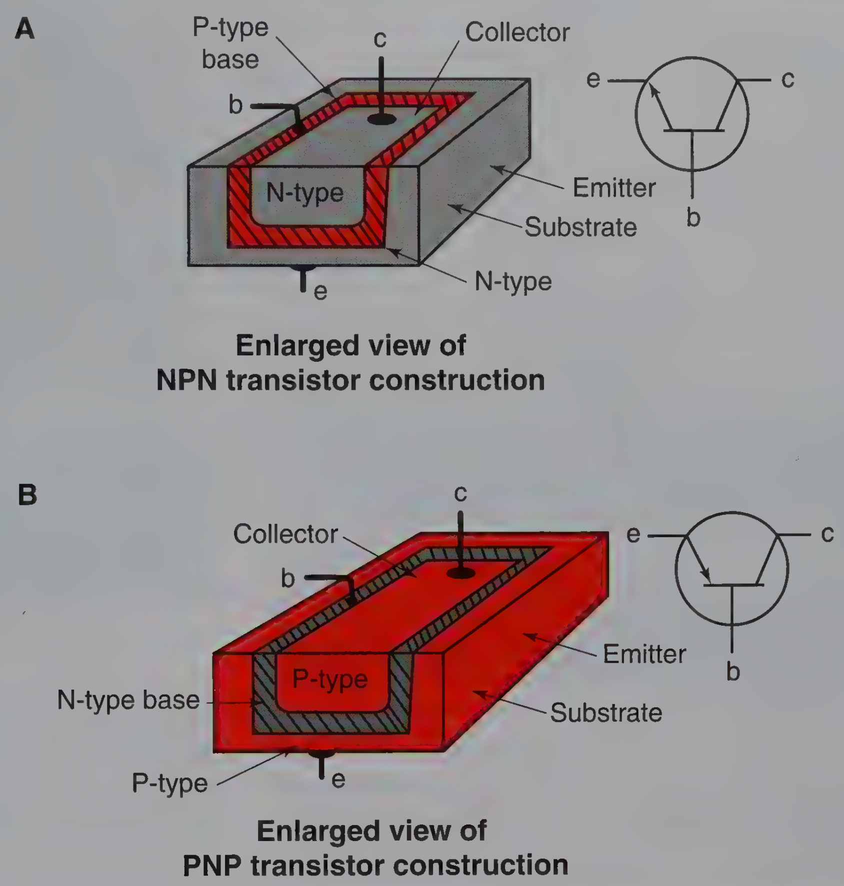
Figure 8-19.
Bipolar transistor construction and schematic symbols are shown. The three junction points are the emitter (e), the base (b), and the collector (c).
A—An NPN transistor.
B—A PNP transistor.



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There are a wide variety of capacitors, but the ceramic disc and electrolytic are the most common. Both work the same way, but electrolytic capacitors can hold much more charge. See **Figure 8-20**.

A capacitor is made up of two conductive plates separated by a thin layer of insulation called a *dielectric*. When a capacitor is connected to a power source, current will flow for a short period of time until the negative plate has gained enough electrons to reach saturation. This negative charge repels electrons from the opposite plate causing it to take on a positive charge. See **Figure 8-21**.

Capacitors can maintain a charge long after the power source is removed. When working with capacitors, it is important to treat them as if they are charged and capable of delivering a shock.

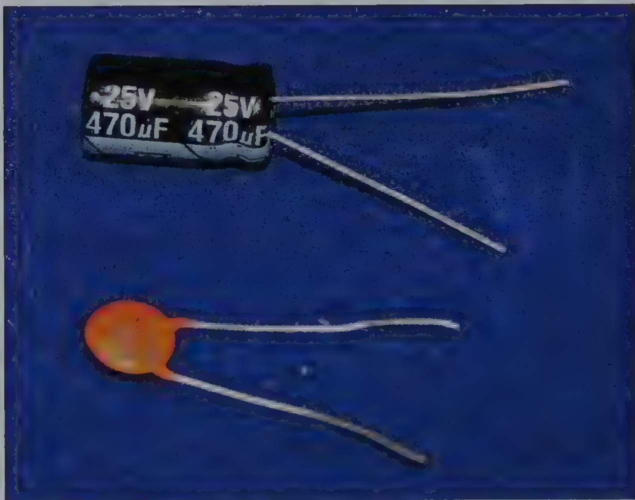

Figure 8-20.
Shown are types of ceramic disc and electrolytic capacitors.

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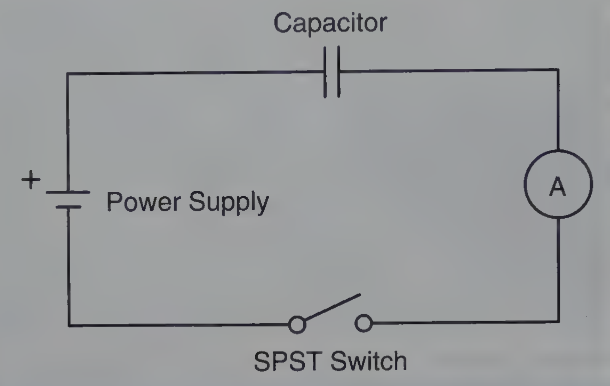

Figure 8-21.

When the switch is closed, the ammeter will read some current flow until the capacitor reaches saturation.

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Figure 8-22.

It is important to take antistatic precautions when working with ICs because they are very sensitive to charge buildup. One type of precaution is this antistatic wrist strap.

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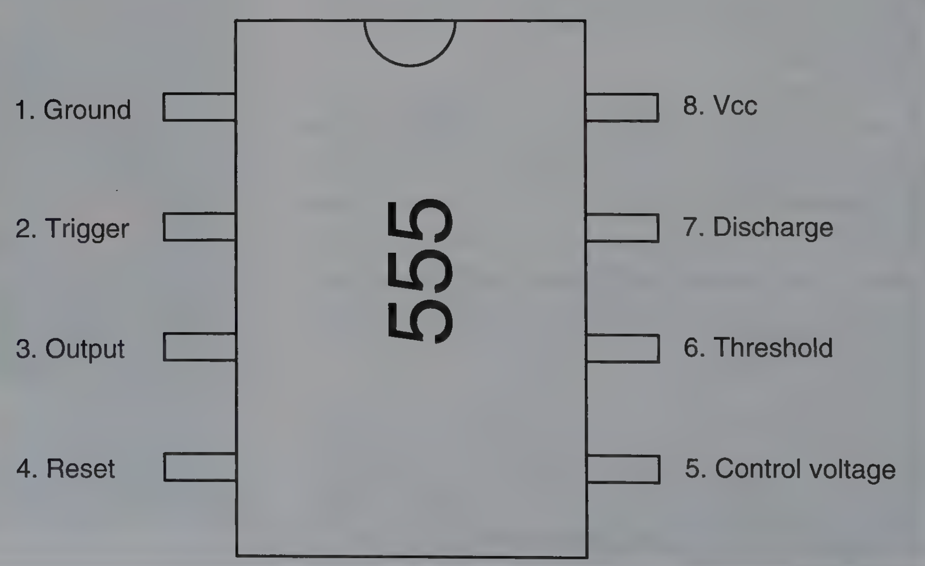
Integrated Circuits (ICs)

An ***integrated circuit (IC)*** consists of multiple electronic circuits etched into a thin layer of silicon and enclosed in a protective material like plastic. A dot or notch on the outside of the chip is used for orientation. ICs contain resistors, capacitors, diodes, transistors, and the conductors to connect the circuits. Some ICs are very sensitive to static electricity, or charge buildup. It is important to take antistatic precautions when working with these ICs. See **Figure 8-22**.

One of the most common ICs is the 555 timer. It includes 23 transistors, two diodes, and 16 resistors. The 555 timer has literally thousands of applications. The 555 can be connected in a circuit in one of two ways: monostable or astable. When used in monostable mode, it creates an output for a given period of time. Think of a seatbelt indicator on a dashboard of a car that turns on to tell the driver to use the seat belt, but turns off after a given period of time. 555 timers can also be used in astable mode, where a repetitive pulse is created. An example of this could be the repetitive buzzing of an alarm clock. **Figure 8-23** shows the 555 timer and its pin diagram.

Figure 8-23.

This diagram shows a 555 timer and pin configuration.



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Semiconductors

Semiconductors are materials with conductive capabilities between that of conductors and insulators. Silicon is the most common semiconductor. Semiconductors are used in items such as transistors, diodes, solar panels, and integrated circuits (ICs).

Sensors

Electronic *sensors* create an electrical signal based on environmental conditions. The signal changes as the environmental conditions change. For example, electronic thermostats are used in many homes to tell the heating system when the house has cooled down and it is time to make more heat. Inside the thermostat is an electronic sensor. This sensor can tell what the temperature is in the home and sends that information through an electrical signal to the heating unit.

Output Components

Output components are the parts that use electricity to perform a desired task. For example, a lamp uses electricity to create light and a motor uses electricity to create rotary motion.

Incandescent Lamps

As electrons flow through a conductor, they create friction and, therefore, heat. Some conductors can get very hot. This heat can be used to generate light. An *incandescent lamp* creates light when the current flow causes the tungsten filament to get so hot that it glows. The tungsten filament is suspended inside a glass globe. All of the air inside the globe is evaluated and is sometimes replaced with an inert gas, such as argon. If there were oxygen inside the globe, the filament would burn up due to the heat. See **Figure 8-24**. Federal energy efficiency legislation has mandated traditional incandescent bulbs be phased out in favor of more efficient devices, such as high-efficiency incandescent, CFLs, and LEDs, which are described below.

Figure 8-24.

This incandescent lamp uses a tungsten filament to create heat, which generates light.

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Gas Discharge Lamps

In *gas discharge lamps*, when the glass inside the globe is ionized. Electrons are released from their bonds and are free to flow. This causes the gas to glow and create light. Neon lamps are an example of gas discharge lamps, but other gases are also used. A resistor must be placed in series with the light to limit current flow because the resistance of the ionized glass is so low. Gas discharge lamps can create the same amount of light as incandescent lamps, using a fraction of the electricity.

Fluorescent Lamps

Fluorescent lamps consist of a long glass tube coated on the inside with phosphorous and filled with an inert gas. There is also a small amount of mercury. At each end of the tube, there is a filament, which creates a small amount of heat to vaporize the mercury. Passing electrical current through the vaporized mercury produces ultraviolet light, which is invisible to humans. The ultraviolet light causes the phosphorous to glow, creating the light we see. It is important to note that fluorescent lamps use much less electricity than incandescent lamps because incandescent lamps waste so much energy in the form of heat.

Compact Fluorescent Lamps

Compact fluorescent lamps (CFLs) work on the same principle as the fluorescent lamps discussed previously, but are designed to fit into normal light sockets. CFLs have been around for quite a while, but recent technological advancements and concerns about global climate change have made them more popular.

CFLs use about 75 percent less energy than incandescent lamps and last up to ten times longer. **Figure 8-25** shows a compact fluorescent bulb.

Light-Emitting Diode (LED) Lamps

Light-emitting diode (LED) lamps are extremely efficient lamps that create light by wiring semiconductor material in a forward biased position. Forward bias is achieved by wiring the negative side of the power supply to the negative (cathode) side of the diode and the positive side of the power supply to the positive (anode) side of the diode. A forward biased direct current is passed through a semiconductor material inside the LED casing, and light is emitted. Since the 1960s, LEDs have been used as indicator lights and in seven-segment displays on devices like digital clocks. More recently, as the technology has advanced, they have been used in traffic lights, automobile lights, and flashlights. LED lamps are low cost, extremely efficient, and last for a long time. Their efficiency and reliability result from the fact that they do not create heat like incandescent bulbs. See **Figure 8-26**.

Motors

You learned previously how generators convert mechanical energy into electrical energy. ***Motors*** work in the opposite way to change electrical energy into mechanical energy. Picture an electromagnet between two permanent magnets. The electromagnet spins until its north pole is lined up with the south pole of the permanent magnet and its south pole is lined up with the north pole of the permanent magnet. By this time, the polarity of the electromagnet has reversed, causing it to be repelled from the permanent magnet and attracted to the other side. In this way, the magnet keeps rotating.

Component Platforms

To use the components previously described, they must be linked together on a platform. The most common type of platform used to create circuits is a circuit board. To experiment before soldering the components together, solderless breadboards can be used.

Circuit Boards

Circuit boards are commonly known as PCBs (printed circuit boards). A rigid piece of insulation (typically fiberglass) is used as a platform for circuitry. Thin copper tracks are laid on the insulation, and electronic components are soldered to the track. See **Figure 8-27**.

Figure 8-25.

CFLs can be used to replace incandescent bulbs, using less energy.

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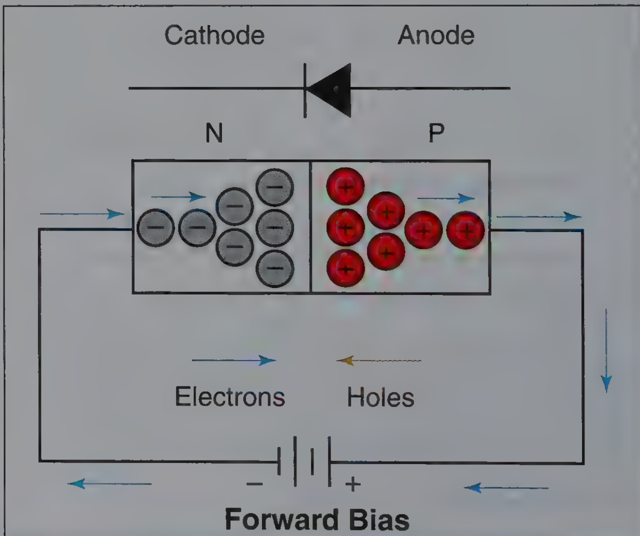

Figure 8-26.

A forward biased direct current can pass through a semiconductor material inside an LED casing to produce light.

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Going Green

Compact Fluorescent Lamps (CFLs)

CFLs are good for our environment because they save energy. If less electricity is used, less electricity needs to be generated. Electrical generation stations that burn fossil fuels contribute to greenhouse gases. Using less electricity means burning less fossil fuels and emitting less greenhouse gases.

The United States Environmental Protection Agency (EPA) recommends that every household replace their five most commonly used lights with Energy Star qualified CFLs. This simple step would decrease greenhouse gases equal to that created by about 10 million cars.

CFLs contain a very small amount of mercury. For this reason, it is best to recycle CFLs rather than throwing them away in the trash. Many waste haulers, power companies, and stores offer CFL recycling. There are also programs that allow you to mail them to a recycler for a fee. Because of the mercury, special care must be taken if a CFL breaks.

New federal lighting standards in the United States require lightbulbs to use about 25% less energy by 2014. This effectively means traditional incandescent bulbs will no longer be made or sold except for specialty applications. High-efficiency halogen incandescent bulbs meet the new requirements. CFLs and LED bulbs are the most common replacement for traditional incandescent bulbs. Linear fluorescent tubes like those commonly found in schools are also required to become more energy efficient. The standards also require that bulbs be advertised by lumens of light emitted rather than wattage, or power consumed. Lumens are the measure of the visible light emitted by a bulb.

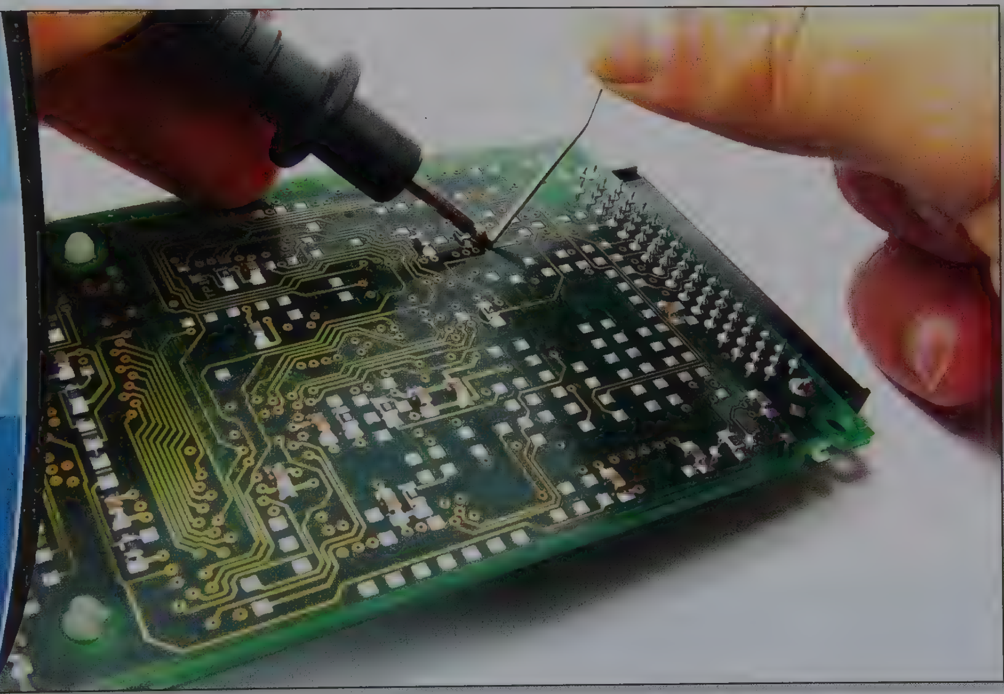

Figure 8-27.
Circuit boards contain copper tracks, to which electronic components are soldered.

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Solderless Breadboards

Solderless breadboards are ideal for experimentation and testing circuits before they are constructed. Components and leads can easily be moved from one place to another because no soldering is required to make connections. See **Figure 8-28**.

Electronic Circuit Simulation

Engineers and technicians can now simulate the performance of circuitry using computer software without ever having to build an actual circuit. Engineers lay out the components they would use on the screen, and the software shows them how it would work. Simulation software saves time and money by speeding up the design and development process and identifying problems early on.

Components in Use

Look at the circuit diagram of a ***continuity tester*** in **Figure 8-29**. When there is continuity between the two probes, the circuit is closed and a sound is heard from the speaker.

The input components in this circuit are the battery, the probes, and the conductors. The battery causes electron flow through a chemical process. The conductors and probes create a path for current to flow.

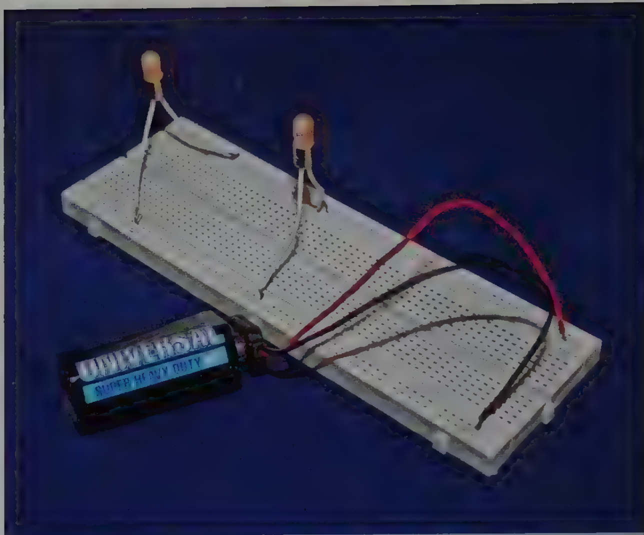

Figure 8-28.

Solderless breadboards can be used to experiment with circuits before soldering to make connections.

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The switch, capacitor, transistor, 555 timer IC, and resistors are all control components. When there is a closed circuit between the probes and the switch is closed, the 555 timer IC generates an audio signal, which is amplified by the transistor and played through the speaker. The resistors limit current flow in the circuit.

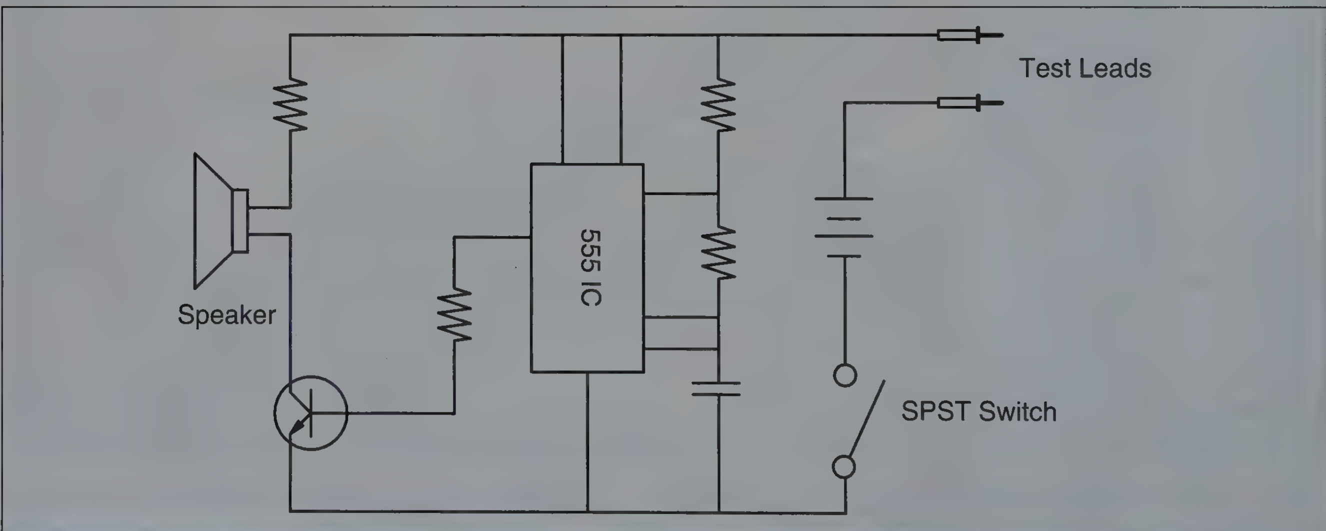

Figure 8-29.

This diagram shows a continuity tester, which helps test for properly working circuits.

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Tools

Meters in Electrical Engineering

Electrical engineers must be competent in the safe and proper use of a wide variety of tools and meters in order to design, build, and troubleshoot electrical circuits and equipment.

Ammeter

Ammeters measure current flow in a circuit in amperes. The circuit must be disconnected so the ammeter can be wired in series and become part of the circuit. Ammeters must be wired in series with the proper polarity. Turn the power off, hook up the meter, and then turn the power back on. Never connect the meter into the circuit with the power on. Never connect an ammeter in parallel with a circuit. Doing so can provide an uncontrolled amount of current to the meter, causing damage to the meter and the circuit or bodily harm to the person holding the meter.

Voltmeter

Voltmeters measure potential differences from one point to another. Voltmeters are always wired in parallel with a device in the circuit. This could be a load or the power source. Always turn the power off, connect the voltmeter, and then turn the power back on before taking a reading.

Ohmmeter

Ohmmeters are used to measure resistance in ohms. Always turn off the power and isolate the part to be tested. Connect the ohmmeter in series with whatever you plan to test. The ohmmeter has its own power supply and tests resistance by applying a voltage to the item to be tested.

Volt-Ohm-Milliammeter (VOM)

Volt-ohm-milliammeters (VOMs) are common multimeters used in electronics. Most are handheld and digital, making them easier to use than stationary or analog meters. VOMs can test voltage, current, and resistance. Many VOMs can also test capacitors and transistors.

Continuity Tester

Continuity is a term used to describe a complete path for current flow. If a circuit is complete, it has continuity. A continuity test can be made with an ohmmeter. Low or no resistance indicates continuity. Infinite resistance indicates an open circuit or a break in the circuit and no continuity. Continuity testers typically beep or use an indicator light if there is continuity. A continuity tester could be used to see if an incandescent lightbulb has burned out. If there is continuity, the light is still good.

Oscilloscope

The ***oscilloscope*** is one of the most widely used electrical test devices because it is so versatile. Oscilloscopes can show the exact shape of a wave on their screens, which will show any possible distortion. They can measure voltage, frequency, pulses, and the timing of multiple signals.

Troubleshooting

See **Figure 8-30** for a schematic drawing of a penlight circuit. The two cells, wired in series, provide about three volts. The diode drops about 0.7 V, delivering about 2.3 V to the LED in forward bias.

To ***troubleshoot*** this circuit, an electrical engineer might start by testing the voltage at the batteries (cells) to see that it is close to 3 V. Then the engineer might go around the circuit with a continuity tester or ohmmeter to make sure there is continuity where there should be. Ohmmeters are used to measure resistance.

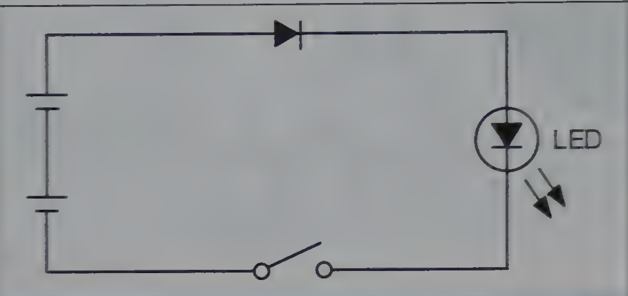

Figure 8-30.

This schematic shows a penlight circuit. Electrical engineers begin troubleshooting by testing battery voltage, then test the continuity throughout the circuit.

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Then the engineer might test the diode to see that it conducts in forward bias but not in reverse. Then he or she might test the switch to see that there is continuity when the switch is closed. The LED can be tested by applying voltage directly to the LED to see if it lights. Keep in mind that a resistor must be used in series with the power source to protect the LED from excessive current.

Electrical Engineering in Action

Electrical engineers might use their knowledge of electrical characteristics, applications, and components to take on a project like increasing automobile efficiency. Gasoline vehicles have poor gas mileage, are expensive to operate, and create tremendous amounts of air pollution. Electric vehicles are much more environmentally friendly but have been slow in development, have limited range, and take too long to charge. So what is the answer?

For answers to most of our modern technological problems, we look to engineers. One concept that has rapidly gained popularity is the ***hybrid car***. Hybrid cars use an internal combustion engine just like a conventional car but also use an electric motor. See **Figure 8-31**. Hybrid cars are quick to fuel, have a range similar to that of gasoline vehicles, and have less of an environmental impact than conventional gasoline vehicles.

One of the great gains of the hybrid car is that it has regenerative braking. When you apply the brakes in a conventional car, the kinetic energy from the car's movement is dissipated in the form of heat caused by the friction of the brakes. With regenerative breaking, this kinetic energy is used to turn the electric motor in reverse, which generates electricity to charge the batteries. This is one of the reasons hybrids get much better mileage than conventional cars.

Hybrids are able to operate with a much smaller gas engine than conventional cars because the gas engine and electric motor can operate at the same time when necessary.

When sitting still in rush hour traffic or at a red light, conventional vehicles idle, wasting gas. But hybrids use no energy at all until the driver presses the accelerator. If battery charge falls below a certain level, the gas engine will automatically charge the batteries.

Fully electric cars do not pollute the air at all (except what could be created when the electricity is generated). The biggest drawback with electric cars is their range because the batteries hold a limited amount of charge. The batteries must be plugged in for hours to get a full charge.

Fuel cell cars produce electricity using hydrogen and oxygen. This electricity is then used to power the car. When a battery runs dead, it must be replaced or recharged depending on the type of battery. A fuel cell works much the same way, but a steady flow of hydrogen keeps it "charged." Fuel cells create zero pollution and the only by-products are water and small amounts of heat.

Most people agree that we need to stop burning fossil fuels in transportation or at least increase the efficiency of the vehicles we are using. The solution to this problem could lie in hybrid vehicles, plug-in electric vehicles, fuel cell vehicles, or some new technology. No matter what the solution, it will require the best and brightest scientists, designers, and electrical engineers to change our world for the better.

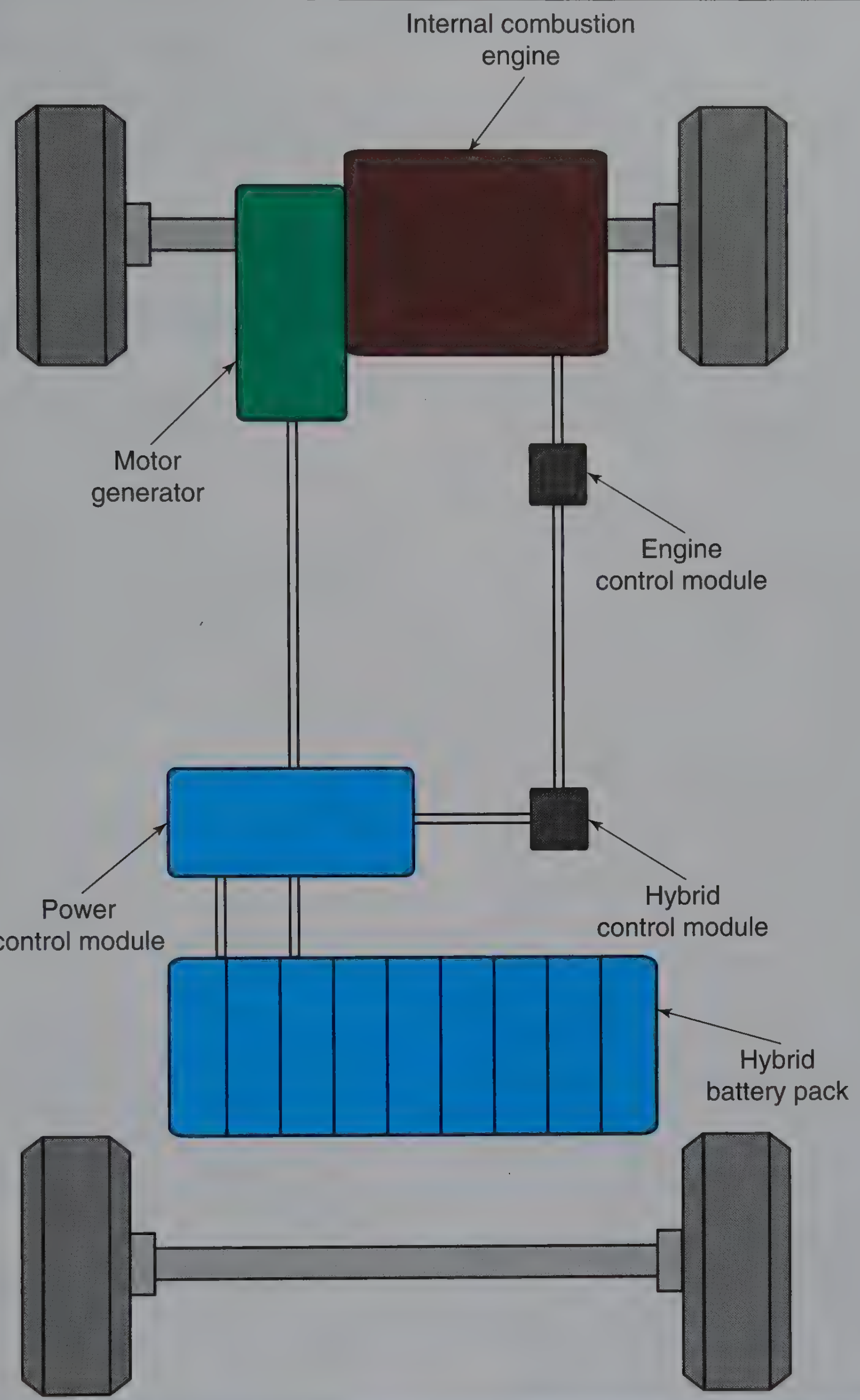

Figure 8-31.

Shown are common parts of hybrid vehicles.

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Summary

- Electrical engineers design, test, develop, and build things like power plants, space shuttle electronics, and electronic gadgets.
- The broadest professional society for electrical engineers is the Institute of Electrical and Electronics Engineers (IEEE).
- All matter is made up of microscopic building blocks called *atoms*.
- Electricity flows through solid pieces of materials known as *conductors*.
- Sources of electricity include magnetism, chemical action, solar cells, and other numerous sources.
- The law of conservation of energy states that energy cannot be created or destroyed. It can only be converted from one form to another.
- Four important characteristics of generated electricity are voltage, current, resistance, and power.
- Ohm's law and Watt's law provide formulas to help find values of voltage, current, resistance, and power within a circuit.
- Three types of circuits are series, parallel, and series-parallel circuits.
- Conductors are a common type of input components in an electrical circuit. Copper and aluminum are the most common materials used in conductors.
- Control components within circuits include insulators, resistors, switches, diodes, transistors, and capacitors.
- Output components of electrical circuits include various types of lamps and motors.
- Circuit boards and solderless breadboards are two of the most common types of component platforms.
- A continuity tester can be used to help in troubleshooting circuits or to ensure circuits are functioning properly.
- The electric motors and other electronic components used in hybrid cars are designed by electrical engineers.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

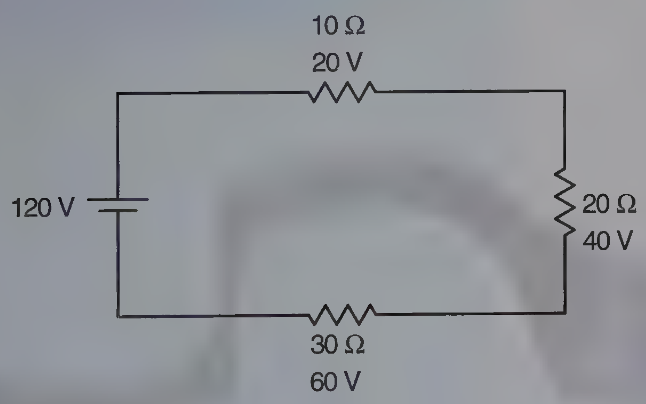
Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is electrical engineering?
2. What level of education is required to become an electrical engineer?
3. High school students should take the highest level courses possible in _____ and _____ if they wish to become electrical engineers.
4. Electricity is the flow of _____.
   A. protons
   B. atoms
   C. electrons
   D. neutrons
5. All matter is made up of microscopic building blocks called _____.
6. Most electricity is produced using electric _____.
   A. motors
   B. electrolytes
   C. cells
   D. generators
7. A battery is an example of which source of electricity?
   A. Chemical action.
   B. Magnetism.
   C. Wind farms.
   D. Solar cells.
8. Electromotive force is another term for _____.
9. _____ are the unit of measure for electrons.
10. When _____ is constant, current flows in only one direction.

11. Which of the following is *not* an example of a good conductor?
    A. Copper.
    B. Aluminum.
    C. Rubber.
    D. Gold.
12. In a circuit where voltage is held constant, if resistance increases, current _____.
13. The unit for power is the _____.
    A. ohm
    B. amp
    C. watt
    D. coulomb
14. _____ is the relationship between resistance, current, and voltage in electrical circuits.
15. A _____ circuit has only one path for current flow.
    A. parallel
    B. series
    C. series-parallel
    D. wave
16. Find the voltage for a series circuit where you know the current is 0.5 A and the resistance is 25 Ω.
17. What is the total current flow in this circuit?



18. Which of the following is *not* an example of a good insulator?
    A. Plastic.
    B. Paper.
    C. Steel.
    D. Rubber.
19. A resistor with a color code of green-yellow-red-gold has a value of _____ Ω with a tolerance of _____%.
20. A(n) _____ allows flow in only one direction and can be used as a rectifier to change ac to dc.
21. _____ is the most commonly used semiconductor material.
22. Incandescent bulbs use a _____ filament inside a globe where the oxygen has been removed.
    A. silicon
    B. carbon
    C. tungsten
    D. fluorescent
23. _____ use about 75% less energy to create the same amount of light as an incandescent bulb.
24. What are PCBs and what are they used for?
25. A(n) _____ can test for resistance and continuity.
    A. voltmeter
    B. ohmmeter
    C. ammeter
    D. oscilloscope

Reinforce learning

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While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Chapter 9

Civil Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- Define *civil engineering*.
- Describe structural forces, loads, and components.
- Identify different types of bridges.
- Understand the structure of a skyscraper.
- Describe the purpose of land surveying.

Key Terms

abutment
arch bridge
beam
beam bridge
bending
brace
cantilever bridge
central core
civil engineering
column
compression
dynamic load
dynamics
electronic distance meter (EDM)
equilibrium
floor joist
free body diagram
geomatics engineering
joint
land surveying
loads
mechanics
piers
roadway
shear
static load
statics
structural analysis
structural frame
structure
struts
suspension bridge
tension
ties
torsion
total robotic station
total station
truss
truss bridge
US Army Corps of Engineers

Practice *vocabulary*

Think of your city or town. Is there a bridge that crosses over a river? Is there a highway or a network of highways in or around your hometown? See **Figure 9-1**. Your town probably has a city water and sewage system. It may even have skyscrapers, subway systems, or other large construction projects. All of these were made possible by civil engineers.

Civil engineering is considered to be the oldest field in engineering. Engineered structures have been found dating back thousands of years. The pyramids built by the Egyptians and the roads and aqueducts constructed by the Romans are early examples of civil engineering. Today, the materials, techniques, and knowledge have changed and evolved but the mission is the same: to build safe facilities that meet the needs of the society.

Civil engineering is the design and construction of public works projects or other large construction projects. Public works projects are construction projects that are financed by governments for use by the public. Roads, bridges, dams, and municipal water systems are all examples of public work projects. Many projects that civil engineers design are used to control natural resources, such as dams and water drainage systems, or to protect shorelines.

Civil engineering is a broad engineering field that includes a number of subfields. Civil engineers work in fields that include structural engineering, water resources engineering, transportation engineering, environmental engineering, construction engineering, and geomatics engineering.

Structural engineers design large structures, such as skyscrapers, dams, tunnels, and bridges. Their focus is to build structures that withstand the dynamics of the natural and human-built world. For example, a bridge must be able to withstand wind, rain, and snow, as well as the weight and movement of automobiles.

Water resources engineers are concerned with the supply and access of water. They design and build canals, city water systems, irrigation systems, and storm water drainage systems. See **Figure 9-2**.

Transportation engineers focus on the safe and efficient movement of people in transportation systems. They design and build road and highway systems with special consideration to the flow of traffic. They may also work on the development of city bus or light-rail systems, or even seaports or airports.

Figure 9-1.
The design and construction of large construction projects, such as highway exchanges, are the work of civil engineers.

rkriminger/Shutterstock.com

Figure 9-2.
The Panama Canal is one of the largest civil engineering projects in the world.

Mat Ragen/Shuttesrtock.com

Environmental engineers are concerned with the environmental impact of structures and human use. They design water treatment plants and solutions to counteract the harmful impact of building projects. See **Figure 9-3**.

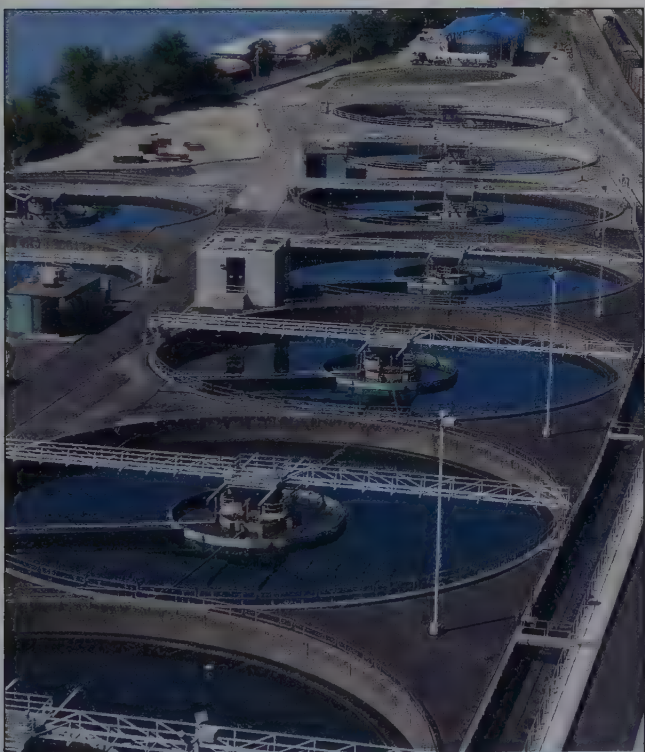

Figure 9-3.
Environmental engineers, a specialization of civil engineering, design sites such as this water treatment plant.

Wade H. Massie/Shutterstock.com

Construction engineers focus on construction sites. They manage, coordinate, and organize the flow of materials and workers in order to stay on budget and on time.

Geomatics engineers measure and collect and analyze information regarding the land, oceans, and natural resources. Geomatics engineers may engage in land surveying, digital mapping, or the use of geographic information systems (GIS) or global positioning systems (GPS).

Professional Aspects

The entry-level requirement for a civil engineer is a bachelor's degree in civil engineering. To earn a degree in civil engineering, courses in engineering topics such as fundamentals of engineering, statics, dynamics, materials, surveying, and engineering design must be taken. The job of a civil engineering technician is another role within civil engineering. Civil engineering technicians work under the direction of a civil engineer and work on many aspects of the design process. Technicians often have associate degrees in civil engineering technology. Civil engineering students typically also take courses in mathematics, such as linear algebra and calculus, and science, such as physics, chemistry, and geology. Courses in one of the specialization areas described above are also required.

History

Municipal Water System Engineering

It has been said that "civil engineering saves lives." This was certainly true throughout history in at least one way that you may not even think about today. The Industrial Revolution drove millions of people from farms into cities. Major cities, like London and New York, became large urban areas. Civil engineers recognized a need to develop systems in cities to provide clean water and remove wastewater to homes.

City water and sewage systems are large public works projects that civil engineers design, construct, and manage. The nineteenth century gave rise to the design and construction of water supply and sewage removal systems in major urban areas. Civil engineers were the designers of these systems. Public water systems first fed water to public squares and later into individual homes. Cast iron and, later, steel pipes were used to carry the water from the source which was often lakes or rivers into the city. In the case of New York City, an aqueduct was built of iron pipe and masonry that in 1842 began supplying the city with fresh water from a location 40 miles north of the city. Today, New York City still gets its water from upstate New York, but it relies on three reservoir systems and a number of lakes and rivers. See **Figure A**. The entire New York City water system supplies over one billion gallons of water per day. The entire system is nearly all gravity fed, meaning that the water flows into the city on its own, without the use of pumps.

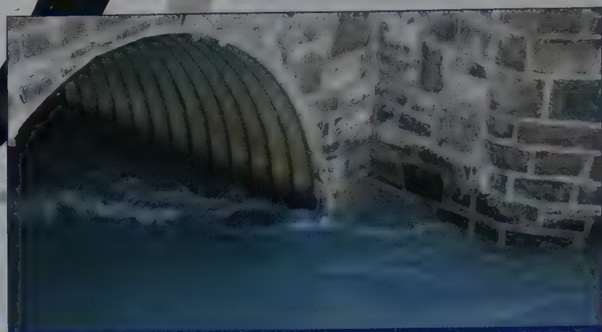

Figure A.

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In the nineteenth century, access to fresh water was only half of the problem. The other half was removing the wastewater. Just as civil engineers built systems to supply fresh water, they designed sewage systems to remove the waste as well. At the time much of the waste was, at best, crudely filtered and fed back into large rivers or lakes. In industrialized nations today, sewage is fed through water treatment plants to be filtered and treated before being discharged into major waterways. Both systems had such an impact on the design of cities that roads were often rebuilt to make room for the complex system of water and sewage pipes.

The access to clean water and the safe removal of wastewater saves lives every day. Prior to these advances, outbreaks of diseases, such as yellow fever and cholera, occurred in urban areas. However, because of the work of civil engineers and the construction of municipal water system, those outbreaks are a thing of the past in industrialized countries and modern cities.

To prepare for civil engineering courses in college, high school students are expected to take courses such as physics, calculus, and other high-level math and science courses.

As professionals, many civil engineers are members of professional societies. The oldest and largest civil engineering society is the American Society of Civil Engineers (ASCE). ASCE was founded in 1852 and currently has over 144,000 members. There are additional, more specialized organizations that engineers may have an interest in joining. These include the International Association for Bridge and Structural Engineers (IABSE), the Institute of Transportation Engineers (ITE), and the American Planning Association (APA).

Civil Engineering Principles

Civil engineering is a broad field of engineering. Because of this, there is a large knowledge base that civil engineers must understand. As civil engineers begin to focus on their specialization areas, their knowledge base also becomes more specialized. For example, an environmental

engineer needs to know and understand different concepts from what a geomatics engineer needs to understand. However, there are some concepts that are fundamental to all areas of civil engineering. The most fundamental knowledge is the understanding of structures.

Structures

A ***structure*** is an arrangement of parts built to remain stable while withstanding forces. The first thing that may come to mind when we think of structures may be a skyscraper or building of some sort. However, bicycle frames, cellular phone towers, boat hulls, and airplane wings are also structures. See **Figure 9-4**. Structures are built to support a specific load for a practical purpose. A bicycle, for example, is built to withstand the weight of the rider and the forces that occur as it is ridden. A shed is built to hold its own weight and the weight of the objects it stores while withstanding elements including wind, rain, and snow.

Figure 9-4.

This structure was designed specifically for communications equipment.

Manuel Fernandes/Shutterstock.com

Structural Load

The forces a structure must withstand are known as ***loads***. Structures are designed to transmit loads from the structure into the ground beneath it. There are two main types of loads: static and dynamic. ***Static load*** is the weight of the structure itself (known as dead load) and weight added to the structure under normal use (known as live load). For example, the static load of a building includes the weight of all of the building materials, furnishings, and people that occupy the building. The static load of a building can be a tremendous amount of weight. Imagine how much just the building materials of a skyscraper weigh.

Dynamic load, on the other hand, is a sudden impact on the structure. A strong wind or earthquake are examples of dynamic loads on a building. Engineers must build structures so the internal forces of the structure counteract the loads (both static and dynamic) that are placed on them. Structures that can oppose external forces and can transfer the load throughout the structure are considered to be in a state of ***equilibrium***. However, when structures are not able to withstand external loads, such as hurricane winds, excessive snow on the roof, or too much weight within the structure, they fail. Structural failure can be very dangerous. See **Figure 9-5**.

Figure 9-5.

Bridge collapse is the result of structural failure.

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Structural Forces

All structures must be built to withstand static and dynamic loads that are applied through several different types of forces. See **Figure 9-6**. The first two forces often act in opposite directions. ***Compression*** is a crushing force down the axis of a material that presses it together, resulting in shortening the material. Standing a paper towel tube on one end and placing books on the open end can demonstrate compression. At some point, the tube will no longer be able to withstand the stress of compression. The opposite force is tension. ***Tension*** is a pulling force that tends to stretch a material. In a tug-of-war contest, the rope must withstand the stress of tension.

Other forces that are applied to structures and structural members include shear, torsion, and bending forces. ***Shear*** forces are forces that act in opposite directions across a material. Imagine, placing a book at the edge of a table and dropping a brick straight down on the book. The shear force is the interaction between the downward force of the brick and the upward force of table. ***Torsion*** is a turning force that is applied to a material or structure. An example of torsion can be found in a screwdriver. As you turn the screwdriver, you are applying a torsion force to the shaft of the screwdriver. You may be able to imagine the amount of torsion force that is applied to a skyscraper during a strong wind. The last force is ***bending*** force. Think of a picnic table. When you sit in the middle of the picnic bench, it will sag in the middle. This is a bending force. When a bending or torsion force is applied to a material, the material is under compression and tension.

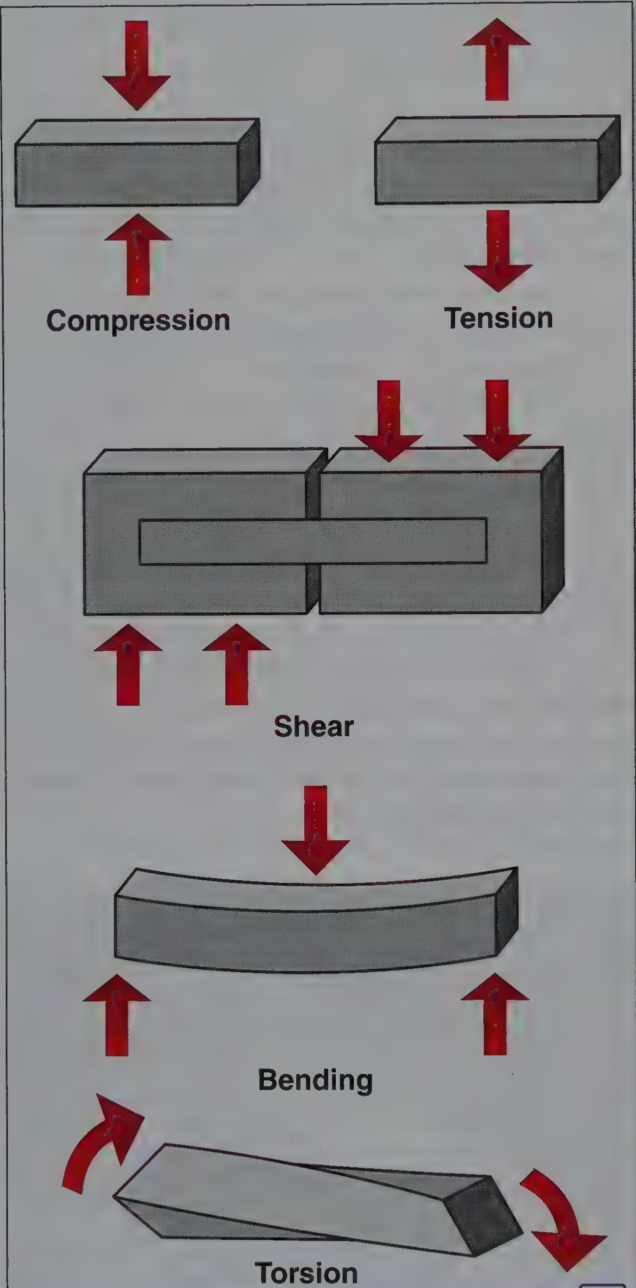

Figure 9-6. Expand learning

Compression, tension, shear, bending, and torsion are the types of forces that structures must be designed to withstand.

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Structural Components

Engineers take into account a number of forces as they determine the best components to use in the structure. Many structures can be broken down into three main elements: beams, columns, and braces. See **Figure 9-7**. ***Beams*** are the structural members that transmit loads to columns. They are used to resist bending. A ***floor joist*** is a beam that is designed to resist bending as people walk across a floor. Beams can take on a number of materials and shapes. In construction, wood and steel I-beams are used. In a bicycle, the top tube is a round tube of metal, aluminum, or even carbon fiber. The load of a beam is often transferred to either one or two columns.

Columns are vertical structural members. Columns transmit the load from above to other structural elements. In the case of buildings,

Figure 9-7.

Structural components, such as beams, columns, and braces, can be seen in this image of scaffolding.

3drenderings/Shutterstock.com

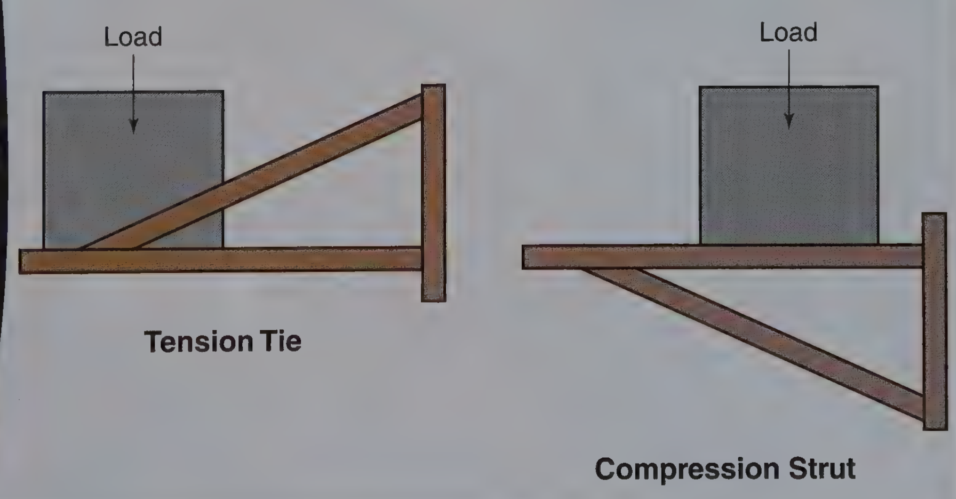
columns transmit the load to the building's foundation. Wood, concrete, and steel are common materials for columns. Columns and beams have been used in construction for centuries. An example of a simple beam and column structure is a dining room table. The tabletop is set on four beams that run from each of the legs. The beams (known as the apron) keep the table from sagging in the middle and transfer the weight of the tabletop to the legs. The legs serve as the columns and support the weight of the table. Other examples include wooden decks, pergolas, and many types of buildings.

While beams and columns handle vertical and horizontal forces, there is often a need for a third structural element. ***Braces*** are structural members that are used to provide structural stability. They are often used to form triangles between beams and columns. The tube that runs from the handle bars to the gears of a bicycle is a structural brace. Braces provide resistance from one of two forces (compression or tension). Braces that resist compression are known as ***struts***. ***Ties*** are braces that resist tension. An example of struts and ties can be found in a wall bookshelf. See **Figure 9-8**.

The final structural component is the structural ***joint***. The joint is the device that connects two or more structural members together. Joints may be rigid or pinned. Examples of fasteners used in joints include bolts, rivets, welds, and glue.

Figure 9-8.

Ties provide structural stability by resisting tension. Struts do the same by resisting compression.



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See **Figure 9-9**. The type of joint has a large impact on how well the structure functions. For example, if the joint that was used was not strong enough to withstand the forces that are applied to the structure, the structure could fail.

Structural Materials

The materials that are selected by civil and structural engineers are an important component of the design. Some of the materials that are used today, such as stone and bricks, have been used for centuries. See **Figure 9-10**. Wood and concrete have also been used for hundreds of years. More recently, the use of steel as a structural material led to the modern skyscraper. All structural materials have advantages and disadvantages based on their properties. For example, concrete has a high strength when in compression, but it has a low tensile strength. Steel has high compression and tensile strength, but it weighs more. Cost also impacts the selection of a material. There are trade-offs with all materials.

Technological and scientific advancements have led to new developments in structural and building materials, which allow engineers to take advantage of new material properties. Reinforced concrete is one example. Reinforced concrete is a structural material that has steel bars within concrete. See **Figure 9-11**. This creates concrete with a much higher tensile strength, as it takes advantage of the tensile strength of the steel. Other structures, not just buildings, have been designed to take advantage of new advances in materials. Many products, including bicycles, use carbon fiber as a structural material because of its low weight and high strength. The space program has created a number of alloys that have specific properties that allow for safe and efficient spaceflight.

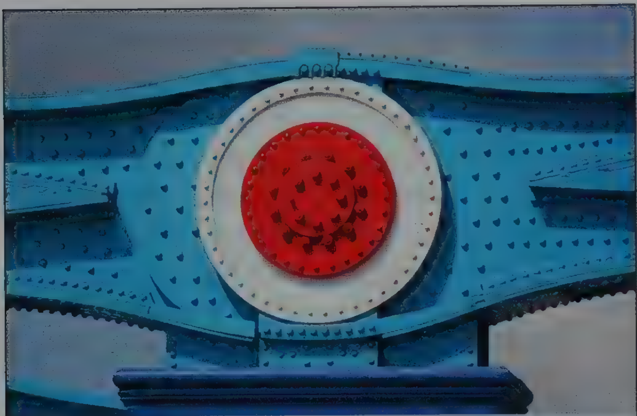


Figure 9-9.

The dots in this picture are rivets, which serve as structural joints in this bridge.

Alexander Cherednichenko/Shutterstock.com

Figure 9-10.

The Coliseum in Rome is an example of an ancient building constructed of stone.

S. Borisov/Shutterstock.com

Figure 9-11.

Concrete is poured over a mesh of steel bars to create reinforced concrete.

Levent Konuk/Shutterstock.com

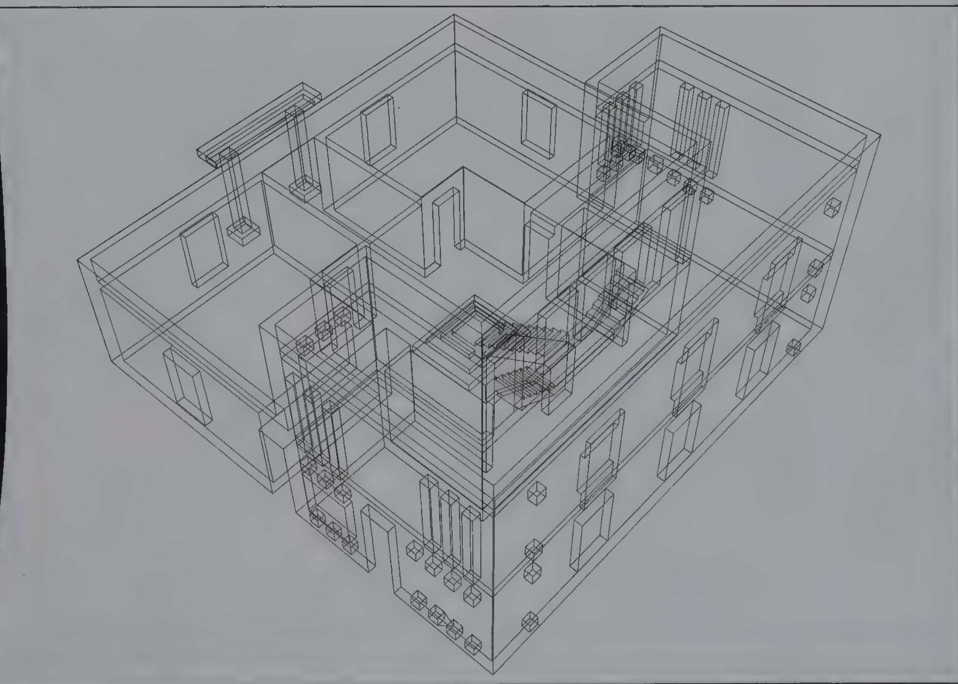
Material properties and material engineering is discussed in greater depth in Chapter 9.

Structural Analysis

One of the roles of a civil engineer who designs structures (often a structural engineer) is the analysis of structures. The goal of ***structural analysis*** is to ensure the structure has sufficient strength and is as efficient as possible. An engineer ensures it will function as needed while making the best use of materials. It is a waste of resources to "overbuild" a structure. Prototypes or mock-ups of simple structures may be built and tested. However, most structures are analyzed using mathematical or computer models with the aid of computer modeling software. See **Figure 9-12**. The mathematical formulas and data that are used to analyze structures are complex. They take into account a number of variables including the properties of the structural members; the strength and elasticity of the materials; and the amount of stress, strain, and load applied to the structure.

Structural analysis incorporates several branches of physics including statics and dynamics. Both statics and dynamics are branches of mechanics. ***Mechanics*** is the study of forces and motion on physical objects. The field of mechanics is used in nearly all engineering disciplines. More specifically, ***statics*** deals with the analysis of loads on objects at rest (or in equilibrium). ***Dynamics*** is the study of forces that cause motion on physical objects. Both are useful in structural analysis.

Figure 9-12. Computers and computer modeling software are used to perform structural analysis on buildings and structures.



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Design

Civil Engineering Software

Civil engineering has been a necessary field for thousands of years. However, the way civil engineers design their projects has changed. One of the most common facets of creating and communicating solutions involves using field-specific computer software.

The computer software helps engineers plan, draw, organize, and even simulate their designs. For example, when engineers draw designs, they can enter some specific values into the design. If the design will not work with the values entered, the engineer will know to change the design before attempting to produce the final solution. They can test specific parts of a design, such as the stress on bridges and the strength of a foundation.

Because there are so many subdisciplines within the civil engineering field, many programs exist that are specific to a type of civil engineering. For example, software can be used in designing pipelines, or it can be used in land surveying. When used in structural engineering, software typically includes symbols for various types of doors, windows, curtain walls, and roofs.

Structural Analysis Example

A basic example of structural analysis can be found in the analysis of a truss. A ***truss*** is used in a number of civil engineering structures from supports for roofs to bridges. The truss shape can even be found in cranes and cellular phone towers. The simplest truss is triangular in shape and is made using structural members that are pinned together at the joints. In roof trusses, the structural members are typically wooden, while bridge trusses are constructed of steel. See **Figure 9-13**.

Figure 9-13.
This preconstructed roof truss is being set in place on top of a structure.

Jim Parkin/Shutterstock.com

There are several forms of analysis that can be conducted on a truss. The first step in the completion of any analysis is to draw a diagram of the truss. The type of diagram most helpful in structural analysis is the free body diagram. A ***free body diagram*** is a simple drawing that includes three components: the structural members and joints, the supports, and the loads or forces that are applied. **Figure 9-14** is an example of a free body diagram of a truss. One piece of information that can be determined based on the diagram is the structural stability of the truss. This is calculated using the following formula:

$$2j = m + 3$$

In this formula, j is the number of joints and m is the number of structural members. If the number of joints multiplied by 2 is larger than the number of members plus three, the truss is unstable. For example, **Figure 9-15** shows a stable and unstable truss and the use of the stability formula.

The next step in structural analysis is to calculate reactions and internal forces. The reactions are the forces that are applied in the opposite direction of the load. For example, imagine that the roof truss in **Figure 9-16** is sitting on top of two walls. If the entire load of the roof is 800 lb, then the total reaction force must be 800 lb as well to maintain equilibrium. This information helps the engineer determine the supports that are needed to maintain the truss.

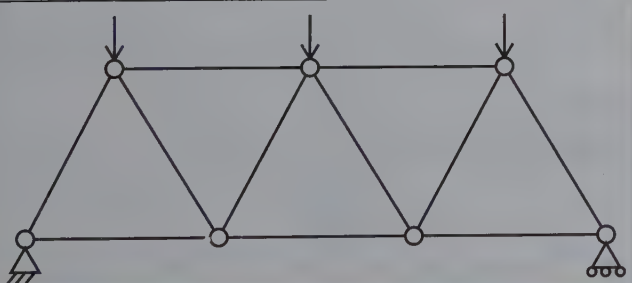

Figure 9-14.

This free body diagram of a truss includes symbols for the structural members (lines), structural joints (circles), supports (triangles), and forces (arrows).

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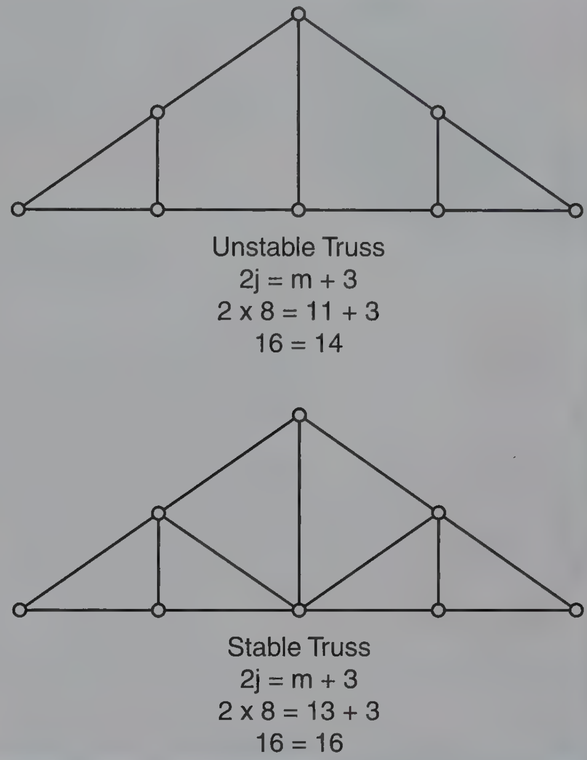

Figure 9-15.

Using the stability formula, a truss can be determined to be either stable or unstable.

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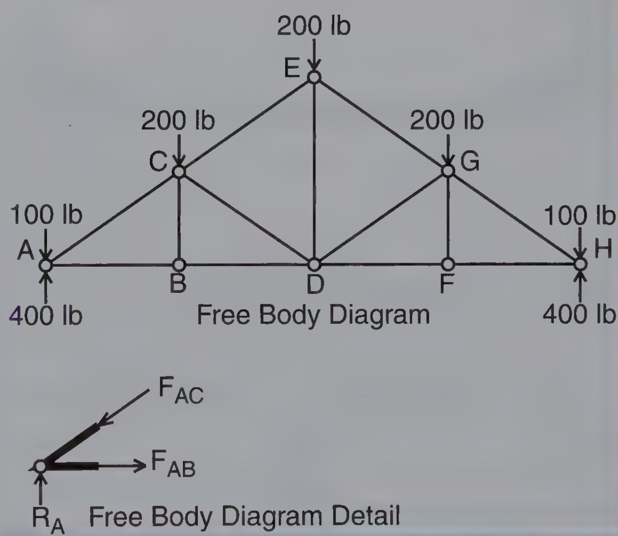

Figure 9-16.

The free body diagram is more detailed and contains the amount and direction of force that is applied to the structure.

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Math

Trigonometric Functions

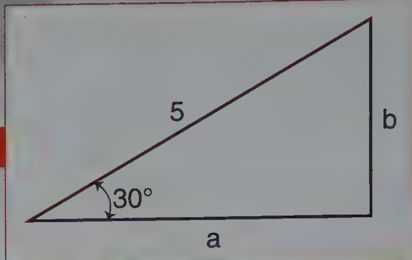

Figure A

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Structural analysis often requires the use of trigonometric functions. The functions can be used to determine missing values of the angles and sides of a triangle. The most commonly used functions are sine, cosine, and tangent. Each of these can be defined by using the sides of a right triangle: the hypotenuse, opposite, and adjacent.

The hypotenuse is the side of the triangle that is opposite the right angle. The opposite is the side that is opposite the angle that is being calculated. The adjacent is the remaining side that has the right angle on one end and the angle of interest on the other.

In terms of the sides of a triangle, the functions are calculated as follows:

- **Sine.** Sinθ = Opposite / Hypotenuse
- **Cosine.** Cosθ = Adjacent / Hypotenuse
- **Tangent.** Tanθ = Opposite / Adjacent

Using a right triangle containing an angle of 30° and a hypotenuse with a length of 5, we will use trigonometric functions to find the remaining sides of the triangle. See **Figure A**.

To find *a*, use the cosine of 30° because it is the adjacent side to the 30° angle, and you know the length of the hypotenuse.

$\cos 30° = a / 5$

$0.866 = a / 5$

$4.33 = a$

To find *b*, use the sine of 30° because it is the opposite side to the 30° angle, and you know the length of the hypotenuse.

$\sin 30° = b / 5$

$0.5 = b / 5$

$2.5 = b$

Use the given information to solve for the missing values in the following problems.

1. A right triangle has an angle of 45°. The opposite side of the 45° angle is 2.
2. A right triangle has an angle of 60°. The hypotenuse of the triangle is 3.5.
3. A right triangle has an angle of 15°. The adjacent side of the 15° angle is 12.
4. A right triangle has an angle of 52°. The opposite side of the 52° angle is 7.
5. A right triangle has an angle of 75°. The hypotenuse of the triangle is 8.3.

Calculating reactions does not provide information on the needed strength of each structural member in the truss. For that information, the engineer must examine the internal forces that are present in the truss. A common method of calculating this is by examining the forces that are present at each joint in the truss. Free body diagrams are drawn for each joint, and the trigonometry functions of sine and cosine are used to determine the load that is applied. The free body diagram for the joint A of the truss in **Figure 9-14** can be seen in **Figure 9-16**.

This analysis, because it is often complex, is usually done by computer software. The truss in **Figure 9-14** was analyzed using computer software to determine the internal forces. The software program calculated the amount of tension or compression on each of the structural members.

It is easy for the civil or structural engineer to change the amount of force in computer program to determine the "worst case scenario." This allows the engineer to determine the correct size of materials to be used for each structural member.

Civil Engineering Applications

Civil engineers, as described earlier, work on different types of projects. Several will be presented in this chapter as applications of civil engineering. Many of the applications of civil engineering are structural and two are discussed in this chapter (bridge and skyscraper design and construction). However, civil engineers also apply their knowledge to work with land and geomatics, which is described later in this chapter.

Bridges

The design and construction of bridges is a common application of civil engineering principles. A bridge can be as simple as a piece of lumber placed on the banks of a creek or as complex as a suspension bridge built to connect two cities over a mile apart. Through designing bridges, you will see that the design of a specific structure must fit within the needs and constraints of the situation. Because bridges are designed to serve a specific purpose, they are almost as unique as the location in which they are placed. Every bridge design takes into account the length of span (the distance between land or structures on each side), the type of foundation, the environment, and the available materials. Once these are considered, the engineer will determine the type of bridge that is best suited for the location. The three common types of bridges are beam, arch, and suspension, and there are also combination and specialty bridges. See **Figure 9-17**.

All bridges share several basic components including piers, abutments, and the roadway. ***Piers*** are the main vertical columns that transfer the load of the bridge into the ground. Piers are placed throughout the span of the bridge.

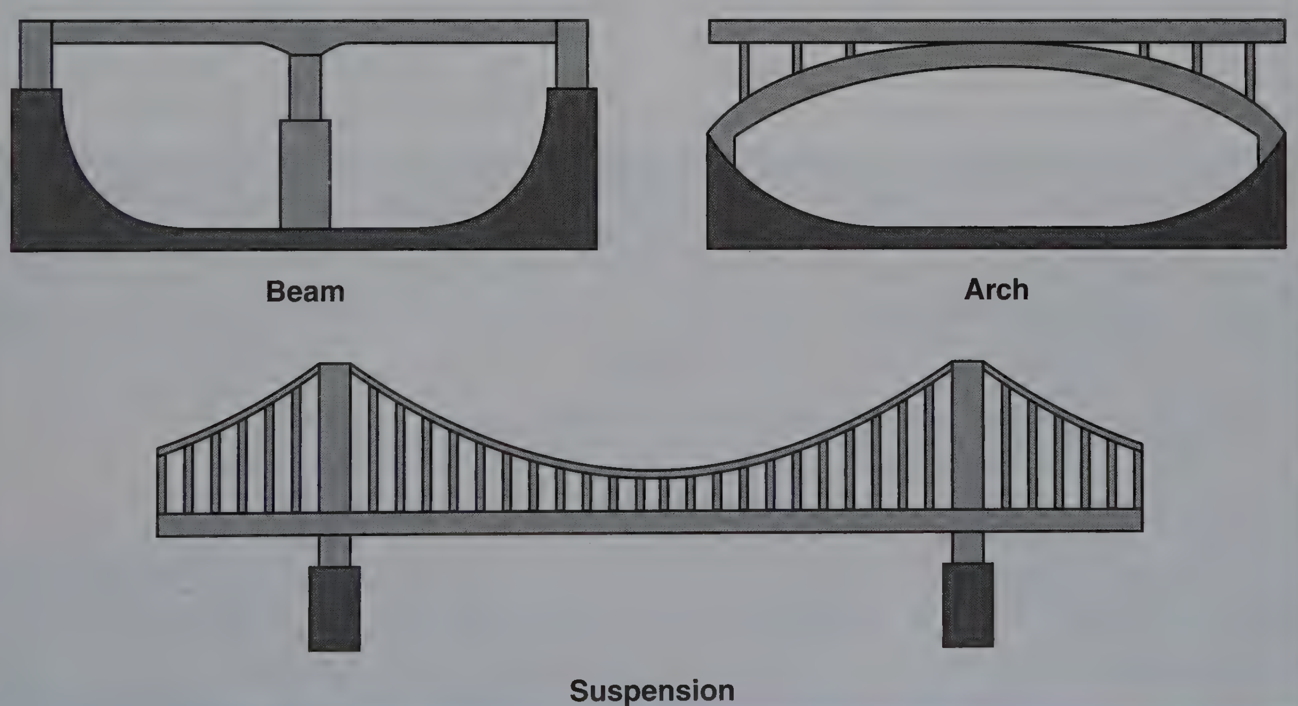

Figure 9-17.

These bridges are the most commonly designed types of bridges.

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Abutments are the structural components that connect the bridge to the ground at the ends of the bridge. The ***roadway*** is the horizontal structure that enables transportation across the bridge. See **Figure 9-18**.

Beam Bridges

Beam bridges are the simplest type of bridge and are used to span the shortest distances. They are the bridges we see most often. Highway overpasses are typically beam bridges in which several steel or concrete beams are placed on abutments. A reinforced concrete slab is placed on top of the steel I-beams as a driving surface. In this type of beam bridge, the beams, abutments, and piers must be strong enough to withstand the forces of vehicles. In a divided highway, there is often a pier in the center of the span to support a portion of the load. Beam bridges can cover great distances if piers can be placed along the length of the bridge. For example, the Lake Ponchartrain Causeway is a 24-mile beam bridge consisting of over 2000 short spans on one lane and 1500 on the other. See **Figure 9-19**.

Figure 9-19.

Lake Ponchartrain Causeway, in Louisiana, is the longest beam bridge of its type in the world.

Gary Fowler/Shutterstock.com

In many cases, especially prior to use of steel I-beams in bridge construction, trusses were used to strengthen bridges. ***Truss bridges*** were popular in the 1800s into the early 1900s. A number of different types of truss bridge designs were developed and used throughout the country. See **Figure 9-20**. The use of a truss in the bridge design allows for the load to be spread out through all of the structural members in the truss. Throughout the truss, each structural member is either in compression or tension as the vehicle weight (or load) is applied to the bridge. Truss bridges were able to span greater distances than traditional beam bridges of the time.

A ***cantilever bridge*** is a type of beam bridge that can span greater distances than a simple beam bridge and often includes trusses in the framework.

Figure 9-18.

The bridge components, such as the abutments, piers, roadway (deck), span, and footings, can be seen in this image.

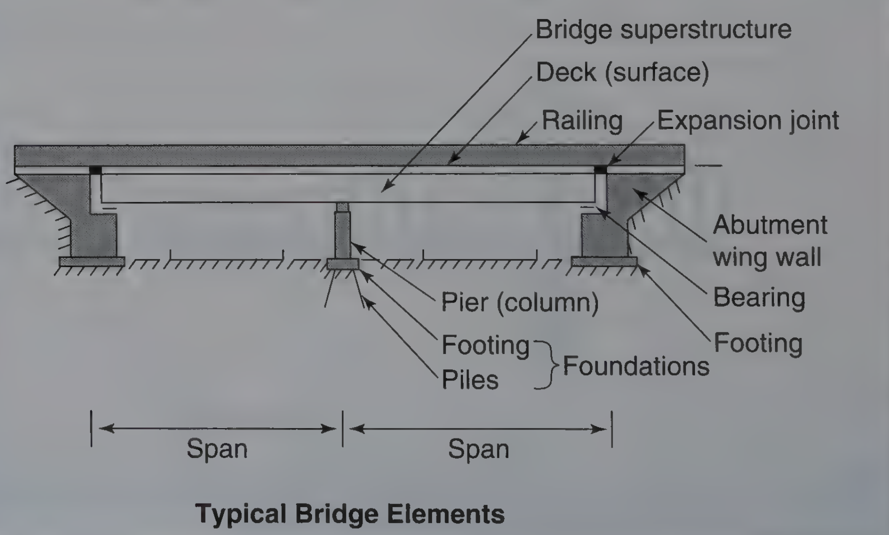

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Figure 9-20.
This is an example of a truss bridge.

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See **Figure 9-21**. Cantilever bridges are named because of their use of a cantilever, which is a structural member that is supported at one end and counterbalanced so it can project outward without support on the other end. Cantilever bridges are generally made up of two cantilevers and one suspended span. Each cantilever section is connected to both the abutment on the bank and a pier that is located a relatively short distance from the end of the bridge. The arm of the cantilever then extends over the river or span to be crossed. The two cantilevers are joined in the center to the suspension span. The suspension span is held up only by the cantilevers. A truss framework is often used on the side of the bridge to transmit the forces throughout the bridge. The bottom half of the bridge controls the compression forces while the top half withstand the tension forces.

Figure 9-21.
This cantilever bridge has six cantilever sections and two suspended spans.

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Arch Bridges

Another type of bridge is the ***arch bridge***, **Figure 9-22**. Arch bridges have been used for thousands of years for both the movement of vehicles and water. Some of the most recognizable ancient arch bridges are Roman aqueducts. Arch bridges rely on the strength and rigidity of the arch. The strength of an arch is that the structural members are always in compression and that it can distribute the load throughout the arch to the abutments. However, because all of the force is distributed to the abutments, they are often massive to withstand the great amount of force. This makes arch bridges impractical in areas that have naturally loose soil or have little rock on which to place the abutments. Arch bridges were built for centuries from stone. Today, they are often built of steel and reinforced concrete. Modern arch bridges have been able to span distances of over a quarter of a mile. For arch bridges that will span great distances, piers can also be used throughout the bridge. This places the arches in succession, decreases the length of arches, and extends the length of the bridge. However, this is often impractical or undesired. The arch of the bridge can either support the deck (or roadway) of the bridge from underneath or above, depending on the criteria and constraints of the bridge design.

Suspension Bridges

The world's longest type of bridge, and maybe the first type you picture in your mind when you think of a bridge, is a ***suspension bridge***. See **Figure 9-23**. The main section of a suspension bridge is similar to an upside-down arch bridge.

Figure 9-23.

The two main cables and ropes used to support the deck are clearly visible in the suspension bridge.

Zastolskiy Victor/Shutterstock.com

Figure 9-22.

The arches on top of the piers are used to support the roadway in this arch bridge.

Dan Costa/Shutterstock.com

However, instead of relying on compression, suspension bridges utilize tension forces. The main components of a suspension bridge are the towers, the main cables, and the anchorages. The towers support the main cables and transmit the load of the bridge into the ground. The cables, generally made of steel, are stretched from each end of the bridge and attached to anchorages that keep the cable in tension. Steel ropes or cable are hung from the main cable and attached to the deck (or roadway). The weight of the roadway is supported by the tension strength of the main cables. A truss system is usually used underneath the roadway to provide structure and stiffness.

Specialty Bridges

While most bridges are one of the three types described above, there are times that a single type does not meet the needs of the engineering design problem. In some situations, a combination of two or more bridge types may be the best solution. In other situations, the construction of a bridge would impact other forms of transportation. For example, a bridge over the Mississippi River may impact ship and barge traffic on the river. In this example, the design situation may call for a movable bridge. Movable bridges have been designed to be hinged, like a drawbridge; swing on a pivot point; and even have entire sections that can be raised to allow for water transportation.

Figure 9-24.

The tallest skyscraper in the world is the Burj Khalifa in Dubai, United Arab Emirates.

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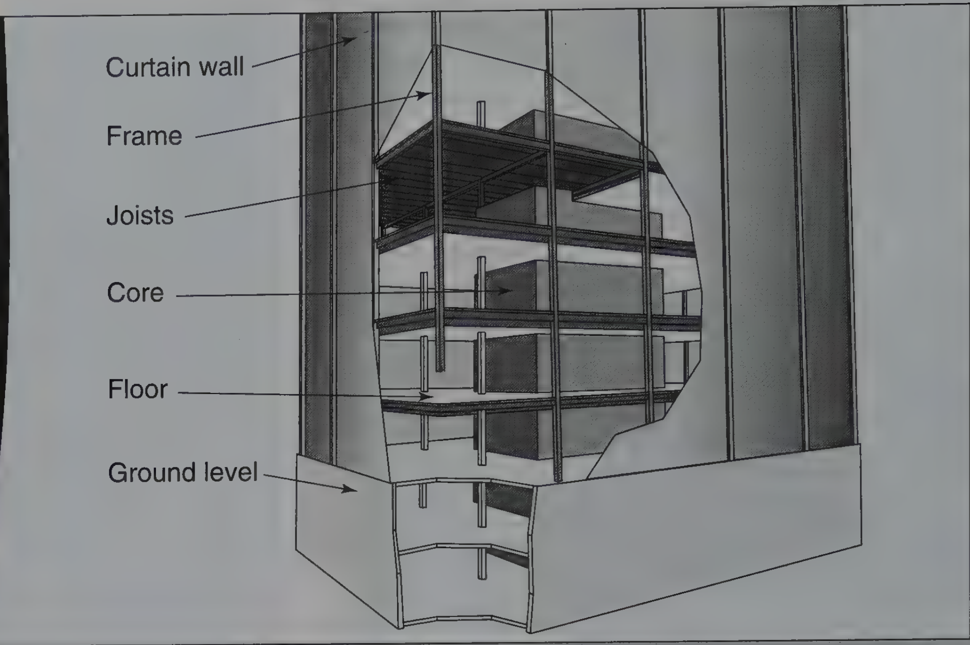
Skyscrapers

Skyscrapers are an American invention that has lead to global innovation. The first skyscrapers were built in Chicago and New York City around the turn of the twentieth century. Those two cities have by far the greatest number of high-rise buildings, but no longer have the tallest. In fact, only three of the tallest 15 buildings in the world are in the United States. The tallest skyscraper is Burj Khalifa in Dubai, United Arab Emirates. See **Figure 9-24**. The spire of the building reaches 2,717′, which is over 1,200′ taller than the roof of the Willis Tower in Chicago.

The building of skyscrapers was made possible by engineering and material advancements that were able to better compensate for weight and wind. As buildings grow in height, their weight increases. In the past, builders made the walls of the lower floors thicker to withstand the load caused by weight of the upper floors. However, in dense urban settings, it was unpractical for the base of the buildings to be as large as would be required to build a skyscraper. To solve this problem, civil engineers began to use iron, and later steel, to construct buildings with columns and beams. This created a ***structural frame***, sometimes called a skeleton. The skeleton was attached to footings and piers that extended deep into the earth. The outer surface of the building then did not have to carry the weight of the structure. The outer surface, known as a curtain wall, can be made of glass, concrete, or a range of other materials. See **Figure 9-25**.

Figure 9-25.
The main components of a skyscraper structure are visible in this graphic.



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The structural system was enough to withstand the dead load of the building. However, it alone could not always withstand the increased live load produced by wind. The taller the building, the more wind it must resist. It must also be more resistant to forces such as earthquakes. To combat this problem, civil and structural engineers designed skyscrapers to have a ***central core***. The central core is usually a reinforced concrete shaft at the center of the building. The structural frame is attached to the core to help the stability of the structure. The central core is also a functional part of the building as it contains the elevator shafts and mechanical systems.

Civil engineers often manage the construction of skyscrapers. The construction process starts with the design and permit phase. Once the design is approved, the site is excavated, and the substructure consisting of the piers and footings is constructed. See **Figure 9-26**.

Figure 9-26.
The construction of skyscrapers or other large construction projects is overseen by civil or construction engineers.

Alison Hancock/Shutterstock.com

The central core and structural frame is then built and later enclosed. Once it is enclosed, the interior work can be completed. The entire construction process of a skyscraper can take 8–10 years, even longer if the design process is included.

Other Structural Civil Engineering Applications

Bridges and skyscrapers are good examples of the work that civil engineers do. However, there are a number of other structures that civil engineers are involved with that allow our modern society to operate. Additional structural applications of civil and structural engineering include dams, tunnels, and even sports stadiums with removable roofs. However, not all civil engineering applications include the construction of buildings and other structures. Geomatics engineering is one area that is not focused on structural engineering.

Geomatics Engineering

Geomatics engineering is often linked to the field of civil engineering. Geomatics engineering is interested in determining the location of objects on the earth. Geomatics engineers use specific tools to determine the location of natural objects such as land masses, rivers, and oceans as well as human-built structures. Geomatics engineers create land and resource maps. They conduct boundary and other land surveys. Geomatics engineers also design and utilize geographic information systems (GIS). One main branch of geomatics engineering is land surveying.

Land surveying is the process of taking and using measurements to determine the exact size and shape of a piece of land. Land surveying techniques have existed for thousands of years. The techniques have been used to measure, record, and divide land all over the world. The work that land surveyors do has its foundations in geometry and trigonometry. The basics of land surveying rely on being able to measure distance and angles (horizontal and vertical).

Throughout history, many tools have been used to conduct surveys. Length, for example, has been measured by land surveyors using rope, chains, metal tape, and light and prisms. Today, both distance and angles can be measured using one surveying instrument, known as a ***total station***. See **Figure 9-27**. A total station includes an ***electronic distance meter (EDM)***, which emits infrared light, and a rotating telescopic instrument. The total station requires at least two people to operate it. The land surveyor stays at the total station and directs it toward a member of the survey team that is holding a survey rod with a prism attached. The infrared light from the EDM is reflected by the prism and the total station calculates the distance. The horizontal angle is determined by the total station measuring the amount that the instrument has been rotated from the first point of the survey (known as the backsight).

Figure 9-27.

This land surveyor is using the lens of the total station to locate the prism that is being held at the desired location. This will enable the surveyor to measure the land and locate structures.

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Going Green

Alternative Energy

As the United States and other developed countries look for ways to produce energy from renewable sources, civil engineers will have a number of important roles in their development. In fact, civil engineers have always been part of the design and development of both renewable and nonrenewable power generation. Civil engineers are often involved in the design and building of large-scale industrial buildings. A power plant, whether it is a coal plant or a nuclear power plant, requires teams of civil engineers to be involved in the design and construction.

Throughout history, civil engineers have been key contributors to alternative energy structures. The Hoover Dam, for example, is one of the greatest civil engineering structures to have been built. See **Figure A**. It is a hydroelectric dam that generates enough electricity for over one million people by harnessing the power of the Colorado River. The construction of the Hoover Dam led to numerous innovations in civil engineering.

Today, wind energy farms are an alternative energy source that involves a number of civil engineers. Civil engineers are involved on-site with the wind farm development and land surveying, the design and building of access roads, construction of foundation pads for wind turbines, and the design and construction of wind towers. See **Figure B**. The same will be true of most large-scale alternative energy sites. Geothermal, tidal, solar, and other green energy power plants will all have the need for civil engineers. Some of the projects may even become civil engineering marvels, as did the Hoover Dam.

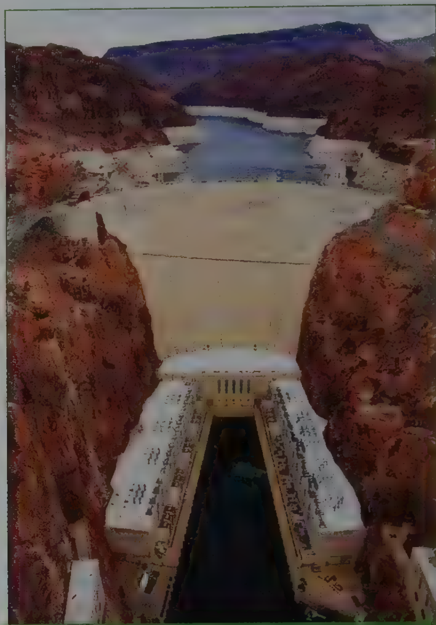

Figure A.

Andy Z./Shutterstock.com

Figure B

ownway/Shutterstock.com

In more recent years, technological advances have led to a device known as a total robotic station. A ***total robotic station*** tracks the survey rod and calculates the distance and angle without the need of the surveyor standing at the station. Once land surveyors have collected data from the field, they use that data to create survey drawings.

There are a number of different survey drawings that can be created depending on the purpose of the land survey. A homeowner may want a boundary survey completed to determine the property lines of their land. A farmer may order a topographic survey, which establishes the elevation of their farm to determine high and low points. See **Figure 9-28**. This could help them to construct a tile system to remove water from their field. A housing developer may order a site plan survey in which the land surveyor completes a boundary and topographic survey so they can determine the best way to subdivide the property. The land surveyor could then create a subdivision plan that divides up the land into smaller lots and creates new roads and sidewalks. See **Figure 9-29**. In large projects, land surveyors often work alongside civil engineers in the planning and design of engineering projects.

Figure 9-28.
Topographic surveys are developed to see the elevation changes and land formations in a piece of property.

alarich/Shutterstock.com

Figure 9-29.
Land surveyors and civil engineers developed subdivision plans when dividing property into smaller sections (or parcels).

Robert Adrian Hillman/Shutterstock.com

Tools

Surveying Bearings

Land surveying is used in laying out buildings, bridges, and other structures. It is also used to record the size and shape of land to be used in determining ownership. Every piece of property that is owned has a legal description that describes the size and shape of the parcel of land using exact details. One method of describing property is using a metes and bounds description. Metes and bounds descriptions start at one corner of the land, known as the point of beginning (POB). The location of the POB is often described by referencing known benchmarks near the parcel of land. Once the POB is located, the distance and bearing of the line that runs to the next corner of the parcel is described. This continues until the entire boundary of the property had been described. A simple example of property description is:

From the point of beginning, thence east a distance of 150′; thence north a distance of 75′; thence west a distance of 150′; thence south to the point of beginning.

In this example the property was 150′ × 75′ square and the property boundary ran directly north, south, east, and west. Most land, however, is not completely square and does not fall directly north, south, east, or west. In these cases, bearings are used. Bearings are a way for land surveyors to express the direction of lines. They use a quadrant system based on north, south, east, and west. When a line is drawn from a point it is in one of the four quadrants (NE, NW, SE, or SW). See **Figure A**. Once the quadrant of the line is determined, the angle must be found. Angles are always measured from the north-south axis. An angle that is 30° from the north-south axis in the NE quadrant would be labeled N 30° E, and a line that runs 65° from the north-south axis in the SW quadrant would be labeled S 65° W. See **Figure B**. Another example of a property description is:

From the point of beginning, thence north 80° east a distance of 200′, thence north a distance of 125′, thence north 71° west a distance of 104′, thence south 80° west a distance of 100′, thence south a distance of 175′ to the point of beginning. See **Figure C**.

The use of distances and bearings allows land surveyors to be exact in describing the boundaries in a legal description or in a survey drawing.

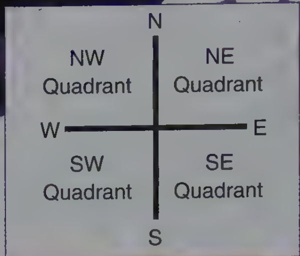

Figure A.

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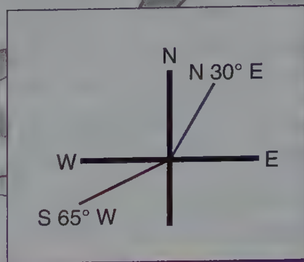

Figure B.

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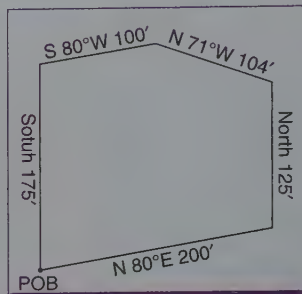

Figure C.

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Civil Engineering in Action

The work that civil engineers do is rarely completed individually. Civil engineers work in teams, offices, and firms that may comprise civil, structural, and architectural engineers as well as land surveyors. The largest employer of these engineers is the ***US Army Corps of Engineers***. The Corps of Engineers was started in the late 1700s with the appointment of a chief engineer to the army. Since that time, the US Army Corps of Engineers has grown into an agency that has built military and civil works throughout the United States and the world. The US Army Corps of Engineers now employs over 34,000 personnel, only a small percentage of whom are military personnel.

The US Army Corps of Engineers has been used in combat to build roads, bridges, embankments, and to destroy enemy bridges. They are also in charge of all military construction, such as military bases, hospitals, and arsenals. The US Army Corps of Engineers has several active and reserve units that can be deployed around the world. They have also been involved in other government projects, including missile sites and national monuments. See **Figure 9-30**.

The greatest impact of the US Army Corps of Engineers, however, may be their civil works projects. A large portion of projects that have been completed by the US Army Corps of Engineers deal with the development, control, and use of water resources. These projects include the design and construction of harbors, ports, canals, and dams. Much of the commercial and recreational use of the Mississippi and Ohio Rivers and the Great Lakes, for example, is due to the work of the US Army Corps of Engineers. Recreation has also been a by-product of another type of the US Army Corps of Engineers water projects. The US Army Corps of Engineers has build and maintains hundreds of dams that are used for either (or both) flood control and power generation. The lakes and reservoirs that have been created by the dams are visited for recreation by millions of visitors each year.

Figure 9 30.

The US Army Corps of Engineers is instrumental in the engineering of many national monuments including The Pentagon.

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Summary

- Civil engineers are involved in the design and building of several construction projects, including roads, water systems, bridges, skyscrapers, and subway systems.
- Civil engineering includes a number of specialized subfields. At least one course in a specialization area is required to become a civil engineer.
- While civil engineering is a broad area that includes several specialization areas, the most fundamental knowledge of all areas is the understanding of structures.
- Structures must be able to withstand various kinds of loads and forces to be stable and safe.
- Many structures can be broken down into three main elements: beams, columns, and braces.
- Some building materials, such as stone and bricks, have been used for centuries. However, technological developments have allowed for structures to be made of wood, concrete, and steel.
- Structural analysis allows engineers to calculate and test whether their designs are safe and efficient.
- All bridges share several basic components, including piers, abutments, and the roadway.
- The building of skyscrapers was made possible by using iron and steel to construct buildings with columns and beams.
- Land surveying is the process of taking and using measurements to determine the exact size and shape of a piece of land.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

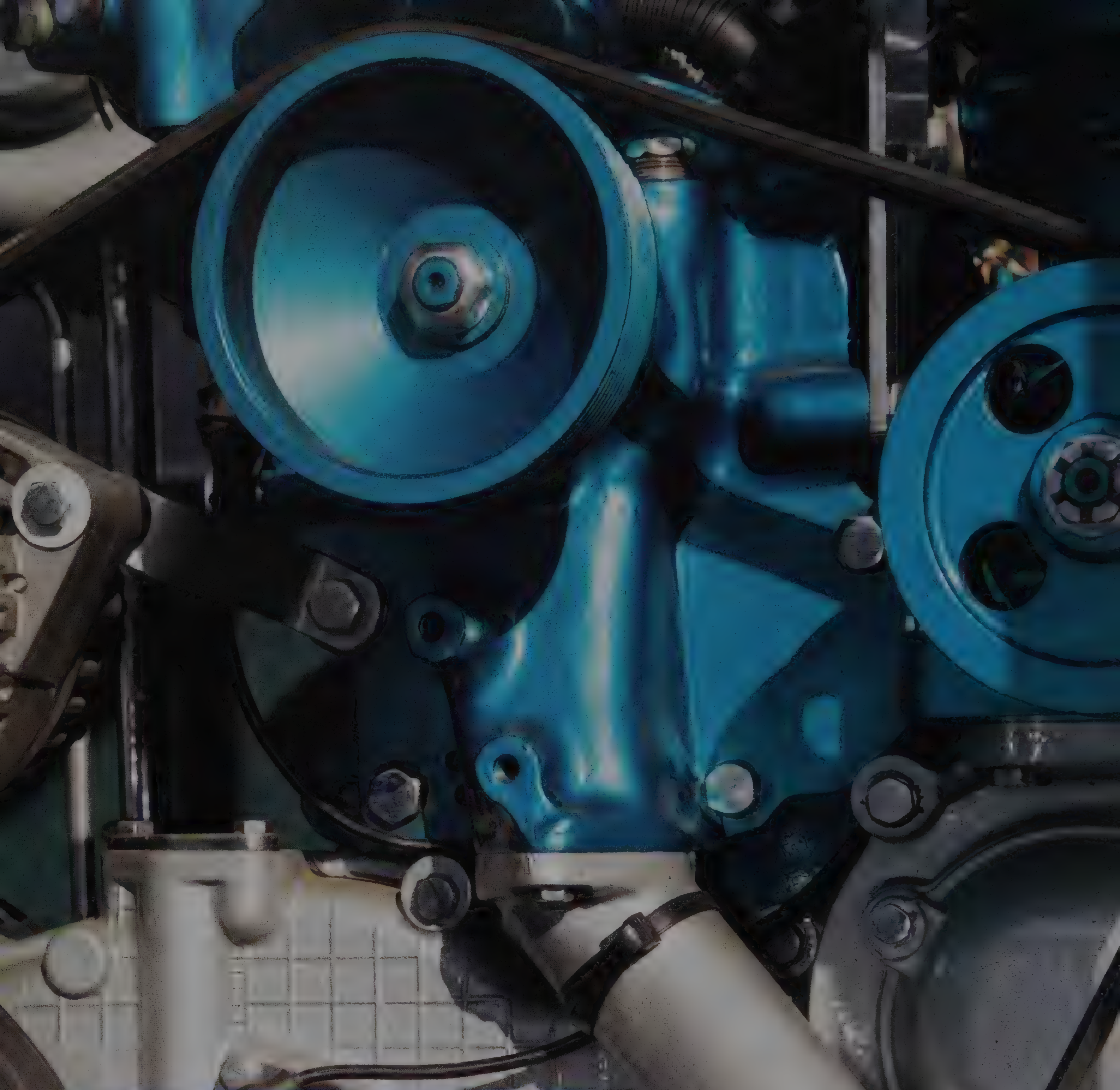
Test Your Knowledge Questions

Answer the following questions using the information provided in this chapter.

1. *True or False?* Civil engineering is a more recent field of engineering to be developed.
2. Construction projects that are financed by governments for the use of its citizens are known as _____ projects.
3. List three subfields of civil engineering.
4. What is the oldest and largest civil engineering society?
5. An arrangement of parts built to remain stable while withstanding forces is known as a(n) _____.
6. Choose whether each example of a load is static or dynamic.
   A. Earthquake.
   B. Building occupants.
   C. Roof.
   D. Hurricane winds.
   E. Structural materials.
7. A crushing or pushing force is known as _____.
   A. torsion
   B. shear forces
   C. compression
   D. tension
8. A pulling force is known as _____.
   A. torsion
   B. shear forces
   C. compression
   D. tension
9. In a structure, the horizontal structural members are known as _____; the vertical members are _____; and the members used to provide structural stability are known as _____.
10. Describe the goal of structural analysis.
11. List two uses for a truss.
12. What is the formula to determine whether a truss is unstable?

13. A typical highway overpass is a(n) _____ bridge.
14. *True or False?* Arch bridges transmit tension forces throughout the arch.
15. Describe how the roadway is supported in a suspension bridge.
16. *True or False?* The curtain wall of a skyscraper does *not* carry the weight of the structure.
17. Describe the purpose of the central core of a skyscraper.
18. Engineers that use tools to determine the location of landmasses, rivers, oceans, and structures are known as _____ engineers.
19. The techniques used in _____ have been used to measure, record, and divide land all over the world.
20. The agency that is instrumental in the control and use of waterways is the _____.

Reinforce learning



While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 10

Mechanical Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *mechanical engineering*.
- Explain the concepts of energy, motion, and simple machines.
- Summarize the components of mechanical and fluid power systems.
- Describe principles of mechanical power.
- Give examples of mechanical engineering applications.

Key Terms

actuator
air compressor
bearing
belt
cylinder
energy
fluid motor
fluid pump
force
friction
gear
gear ratio
horsepower
hydraulic system
inclined plane
kinetic energy
lever
linear motion
mechanical advantage
mechanical energy
mechanical engineering
Pascal's law
pneumatic system
potential energy
power system
pulley
reciprocating motion
rotary actuator
rotary motion
screw
shaft
simple machine
torque
valve
wedge
wheel and axle
work

Practice vocabulary

Each time you ride in an automobile, turn on an air conditioner, use a cordless drill, or travel on an elevator, you are using products that have been designed, built, or somehow influenced by a mechanical engineer.

Mechanical engineering is the designing, building, and maintenance of mechanical and fluid systems. Mechanical engineering is one of the largest, broadest, and oldest engineering careers. In terms of size, there are over one quarter of a million mechanical engineers working in the United States. These engineers work on products that cover a wide range of scale, from designing and producing nanotechnology products at the microscopic level to maintaining large power stations. See **Figure 10-1**.

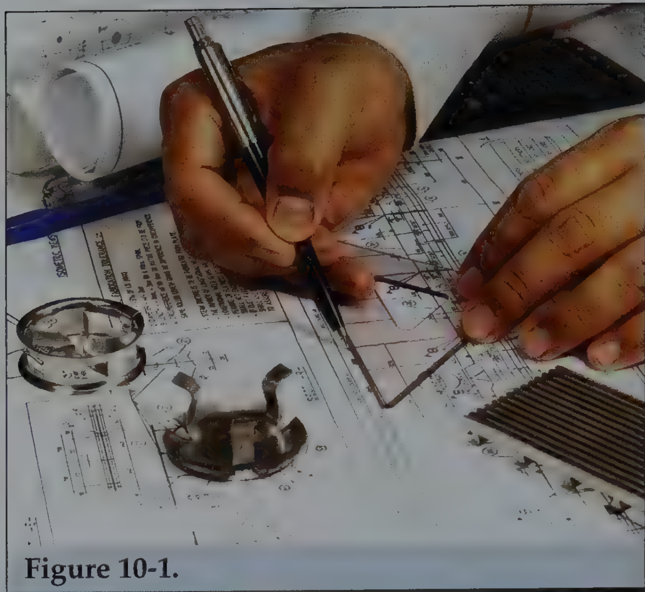

Figure 10-1.

Mechanical engineers design a range of products and systems.

RAGMA IMAGES/Shutterstock.com

Concepts related to mechanical engineering were utilized in ancient civilizations. One early mechanical invention, Archimedes' screw pump, can be traced back to over 2000 years ago. Archimedes' screw pump was designed to move water. It consists of two main components: a screw and a cylinder. The screw is placed inside the cylinder, and one end is placed in water. As the screw is turned, the water is raised by the cylinder.

The Industrial Revolution began with the mechanical invention and application of the steam engine. See **Figure 10-2**. For over 100 years, mechanical engineering has been taught in colleges and schools of engineering. Today, many of the products that have changed our lives and led to the technological world that we live in can be credited to mechanical engineers.

Figure 10-2.

The invention of the steam engine, used in locomotives, led to the development of the mechanical engineering field.

Phillip Minnis/Shutterstock.com

Mechanical engineers design, build, and maintain such products as tools and machines; engines and turbines; heating, cooling, and refrigeration systems; vehicles; and household products and devices. Mechanical engineering is so broad that mechanical engineers often select a specialty, such as engine design or air conditioning systems, and focus on the concepts related to their chosen field throughout their careers. Specialization areas are often selected while engineers are working toward their engineering degrees. Often within their specialties, engineers will select a role that focuses on one of the following aspects: research, design, manufacturing, repair, or management.

Professional Aspects

The entry level requirement for mechanical engineers is a bachelor's degree. Most mechanical engineers have degrees in mechanical engineering, but some have degrees in other engineering specialties. To earn a degree in mechanical engineering, courses must be taken in the fundamentals of engineering, statics, dynamics, robotics, mechanics, thermodynamics, calculus, and physics. Computer and design courses, as well as internships, are also common in mechanical engineering programs.

Another job track within mechanical engineering is the role of the mechanical engineering technician. Mechanical engineering technicians generally have an associate's degree and are under the direction of an engineer. Mechanical engineering technicians assist engineers by completing drawings and models and by conducting research and tests.

There are several professional societies available to mechanical engineers. The broadest is the American Society of Mechanical Engineers (ASME). Mechanical engineers that specialize in vehicle design may choose to belong to SAE (formerly known as the Society of Automobile Engineers). Both ASME and SAE have over 100,000 members and publish research journals, conduct conferences and training sessions, and produce professional standards. Other organizations also exist for other specialties of mechanical engineers. Those include American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the National Association of Power Engineers (N.A.P.E.).

Principles of Mechanical Engineering

There are a number of principles that are fundamental to the job of a mechanical engineer. The foundations to these principles are the concepts of force and work. ***Force*** is the push or pull on an object resulting from contact with another object. When we close a car door, throw a baseball, or pull a wagon, we use force to move an object. See **Figure 10-3**.

Figure 10-3.
Force is the pushing or pulling on an object that is required for a mechanical system to operate. In this image, force is needed to move the vehicle to a gas station.

Vuk Vukmirovic/Shutterstock.com

Mechanical tools require the application of force to accomplish work. ***Work*** is defined as the application of force to move an object a distance. Work only happens while a force is being applied and movement occurs at the same time. Work cannot be accomplished without movement of an object. For example, when you ride a bicycle to a friend's house, you are moving the bicycle and accomplishing work. But if you were to position the bicycle against the wall, even though you would be using force against the pedals, work would not be accomplished because the bicycle is not moved over a distance. Work is expressed mathematically as work (w) is equal to force (f) multiplied by distance (d), or $w = f \times d$. See **Figure 10-4**.

Figure 10-4.

This automotive technician applies force to a ratchet to move it, producing work.

Sudheer Sakthan/Shutterstock.com

While mechanical tools are used to complete work, it is also important to be able to measure the amount of work. To measure and evaluate work, we use the term *power*. Power is the rate at which work is performed or energy is transmitted. Generally, power is calculated by dividing the amount of work by the time that it takes to perform the work. Power is expressed mathematically as power (p) is equal to work (w) divided by time (t), or $p = w / t$.

Energy

Energy is the ability to do work. All mechanical tools need an energy source to do work. An automobile engine needs a fuel source to operate the many different components of a car, just like a bicycle needs a human energy source to pedal up a hill.

The different types of energy are potential and kinetic. ***Potential energy*** is energy that is stored and waiting to be used. The energy that is found in stretched rubber bands is an example of mechanical potential energy. This "stored" energy is waiting to be used. ***Kinetic energy*** is energy in motion. Once the rubber band is released, the potential energy is converted to kinetic energy. Examples of kinetic energy include gears turning in an engine, fluid moving through a hydraulic pump, and the radiant heat from the sun warming our summer days.

While potential energy does not produce work, when combined with technological tools, work can be accomplished. For example, springs are often used in mechanical systems because of their ability to convert potential energy into kinetic energy. See **Figure 10-5**.

Mechanical Energy and Motion

The previous example is an illustration of mechanical energy. Energy in motion that uses mechanical devices for conversion is called ***mechanical energy***. Mechanical devices may be levers, wheels, gears, pistons, or more complex tools, such as an internal combustion engine. Mechanical engineers are concerned with the conversion of energy using mechanical means.

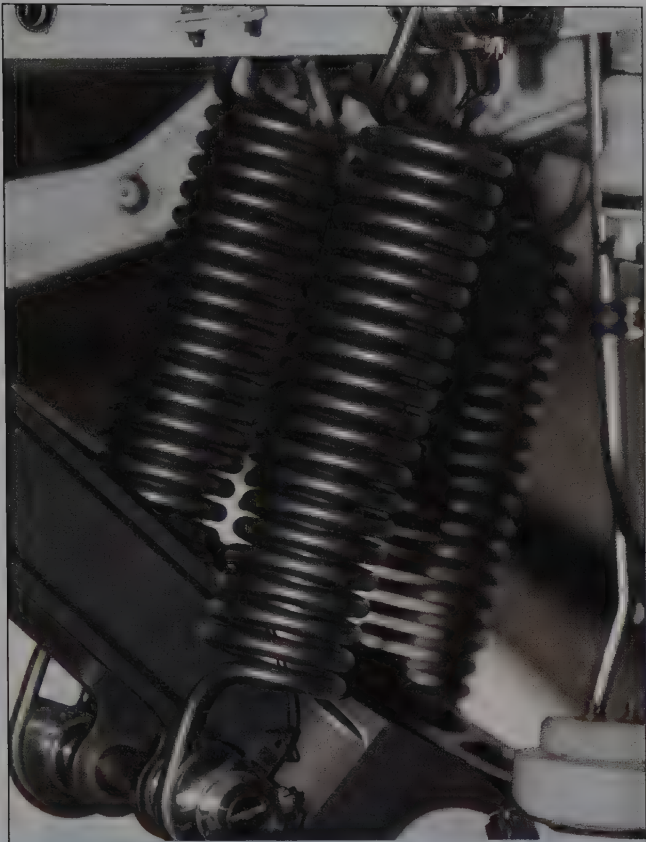

Figure 10-5.

Springs are a common mechanical component.

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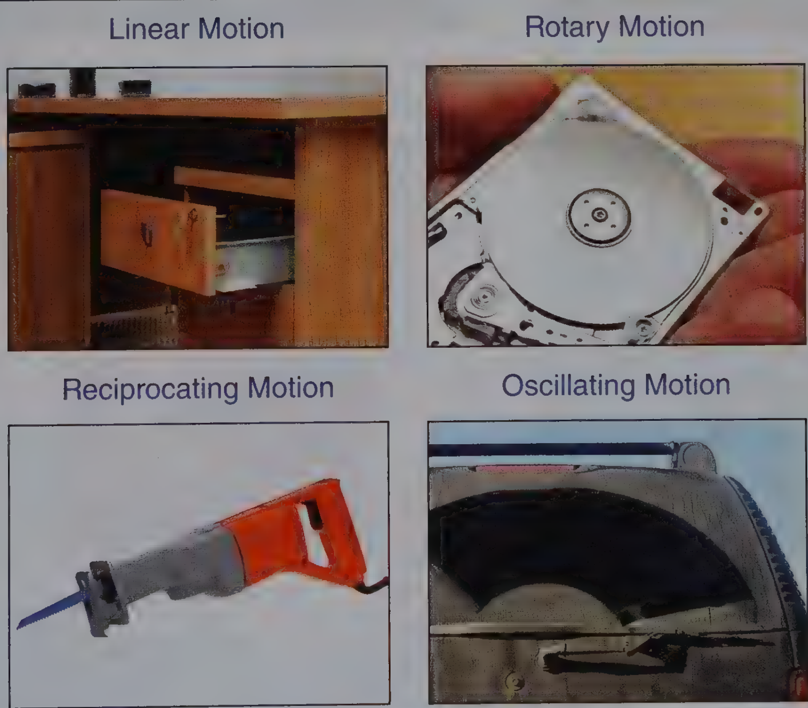
The conversion of mechanical energy often takes place in a power system. ***Power systems*** take energy and convert it into power to accomplish work. Many times this conversion process uses multiple power systems to convert the energy into useful work. Power systems can be electrical, fluid, or mechanical. Mechanical engineers deal primarily with mechanical and fluid power when they are designing and developing power systems. Mechanical power systems are often used to convert one type of motion into another type of motion.

Mechanical power systems use one of six different types of motion. See **Figure 10-6**. The first form of motion is linear. ***Linear motion*** is movement in a straight line. Another form of motion is ***rotary motion,*** which is any motion that moves in a circle. Many times, rotary motion is connected to intermittent motion. Intermittent motion is when movement starts and stops regularly. ***Reciprocating motion*** is linear back-and-forth motion. Oscillating motion is rotary back-and-forth motion that uses a single pivot point. The last type of motion is irregular motion. This occurs when the movement does not follow a constant pattern.

Figure 10-6.

These images provide examples of several types of motion.



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In many situations, several types of motion are used together in a system. For example, a piston in an engine is an example of reciprocating motion. The motion that is created is transferred to rotary motion at the crankshaft. The rotary motion is used to power a number of systems in an automobile.

The objects that are in motion will move indefinitely unless something slows them down. ***Friction*** is a force that acts against motion when two surfaces rub together. Friction can be seen when you roll a ball on the ground and it gradually slows down, but it can also be seen when you throw a baseball to a friend. The air acts as resistance, along with gravity, on the ball until it comes to a complete stop.

Simple Machines

The fundamental concepts of most designs developed by mechanical engineers rely on six simple machines. ***Simple machines*** are tools that make work easier. They include the lever, inclined plane, wheel and axle, screw, wedge, and pulley. See **Figure 10-7**. Mechanical engineers use simple machines to provide a mechanical advantage. ***Mechanical advantage*** is the number of times a machine or tool multiplies the input force to move a load. This is why simple machines make it easier to do work. They can transform the input force by increasing the distance. For example, if you use a ramp (inclined plane) to move a

Figure 10-7.

The lever, inclined plane, wheel and axle, screw, wedge, and pulley are the six simple machines utilized by all mechanical systems.

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refrigerator, the force that is applied is decreased because the distance you have to push the refrigerator is increased.

A ***lever*** is a simple machine that uses a stiff bar rested on a fulcrum, or pivot, to lift or move a load. The closer the object is to the fulcrum, the easier the load is to move. Levers are categorized in three different classes, depending on the location of the input force, the fulcrum, and the load. See **Figure 10-8**.

In a first-class lever, the fulcrum separates the load and the force, which are moving in opposite directions. An example of a first-class lever is a crowbar to pull nails. A second-class lever has a load in the middle of the liver with the fulcrum and force on the two ends. One example of a second-class lever is a wheelbarrow. In a wheelbarrow, the wheel acts as the fulcrum, the load is the object placed in the wheelbarrow, and the force is the lifting force of the operator. A baseball bat is an example of a third-class lever, in which the fulcrum (batter's hands) is at one end, the force (swinging force) is in the middle, and the load (baseball) is at the other end.

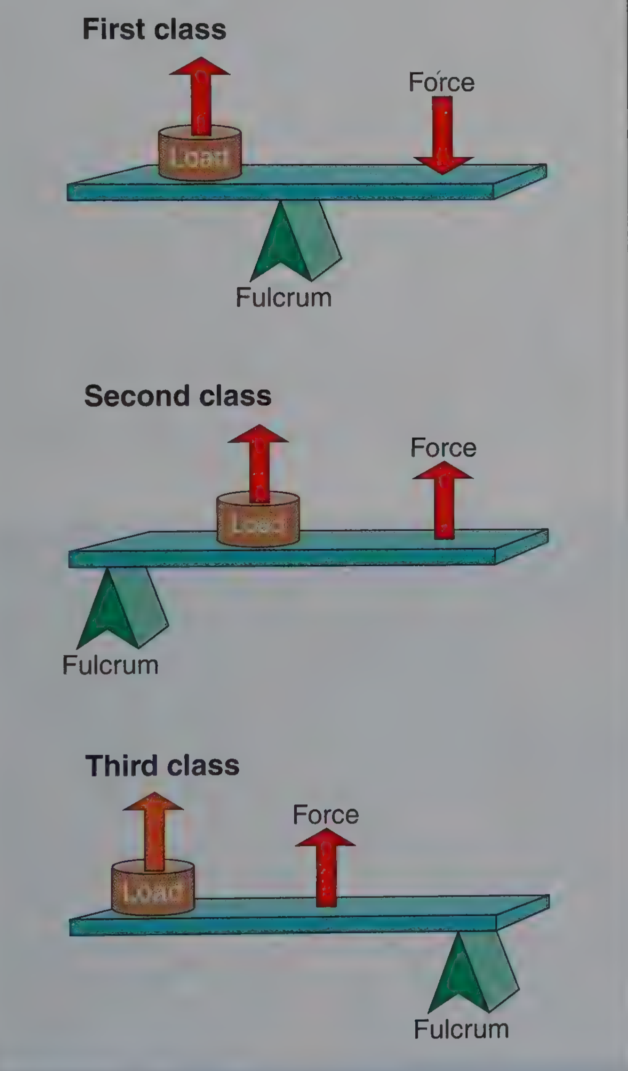

Figure 10-8.

The relative positions of the load, force, and fulcrum determine the class of lever.

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An ***inclined plane*** is a simple machine that uses a flat surface that is higher on one end. A mechanical advantage is gained by moving the object a longer distance while using less force. An example of an inclined plane is using a ramp to load a heavy box onto a trailer. Instead of lifting the box onto the trailer, the ramp serves as an inclined plane to push the box onto the trailer.

A ***wheel and axle*** uses a circular wheel with an axle in the middle to create a mechanical advantage. The gears we use in our machines, waterwheels used to generate hydroelectric power, and even steering wheels are examples of wheels and axles.

The screw is a simple machine that is adapted from another simple machine to provide its mechanical advantage. A ***screw*** is an inclined plane wrapped around a cylinder. We use screws to hold objects together. Screws are also used in clamps to adjust pressure and are used to attach a lid to a jar.

Another adapted simple machine is the wedge. A ***wedge*** is a combination of two inclined planes. When we use an axe to chop wood, a fork to eat our meals, or a stop to hold a door open, we are using a wedge.

The final simple machine is the pulley. A ***pulley*** is a wheel and rope used to move objects. A single pulley allows you to move an object into a different location, but it does not provide mechanical advantage because the amount of force needed to lift the load is the same as the input force. Using multiple pulleys improves the mechanical advantage. Pulleys lessen the amount of force by increasing the distance you need to pull the rope.

To gain mechanical advantage, many mechanisms use simple machines to transmit power. Compound machines use multiple simple machines to transfer power. Examples of compound machines, such as the vehicles we drive, are often complex systems that make work easier.

Statics and Dynamics

A fundamental area of study for mechanical engineers is the area of mechanics. Mechanics is the study of forces and motion on physical objects. There are several important areas of study within mechanics, including statics and dynamics. In a basic sense, statics is concerned with the study of objects at rest, and dynamics is the study objects in motion.

In statics, engineers study how loads are applied to stationary objects. There are two main types of loads: forces and moments. Forces are loads that move an object in a linear direction (push or pull). Moments are rotational loads, or twisting forces. Engineers use statics to analyze the pushing, pulling, and twisting forces that are applied to objects.

Dynamics are used to study the motion of objects (also known as kinematics) and the effects of forces on the motion of objects (known as kinetics). Newton's laws of motion, acceleration, velocity, momentum and vectors are all important concepts in the study of dynamics. Dynamics could be used to determine the stopping power needed for disk brakes or to determine the loads that are applied to a propeller.

Example of Mechanical Engineering Principles

Mechanical power systems connected to other power devices help us accomplish work on a daily basis. One example of using these systems together to complete a task is when you ride a roller coaster at your favorite amusement park, **Figure 10-9**. A roller coaster illustrates most of the previously discussed factors involving energy and power. First, you sit in the roller coaster on the ground, ready and excited to begin your voyage. An electric power source is connected to a series of motors. These motors take the electrical energy and convert it to mechanical energy to begin your climb to the top of the track. As you ascend, this mechanical energy is transferred through many mechanical devices to operate the chain drive that pulls the carriage to the highest point on the roller coaster. This series of chains,

Figure 10-9.
Roller coasters include a number of mechanical systems that are combined to make an exciting and thrilling ride.

Rafael Ramirez Lee/Shutterstock.com

gears, and pulleys takes the mechanical power and accomplishes work by moving the carriage to the top. Once you reach the highest peak of the tracks, the carriage has gained potential energy. The carriage resting at the top of the track is waiting to use gravity to convert the potential energy into kinetic energy.

Once the carriage you are riding begins to move down the slope, you can feel the potential energy being converted to kinetic energy. By using the gravitational force as a source of power, the energy in the coaster becomes kinetic energy. The wheels of the roller coaster combine with the track to create a mechanical system. This mechanical system accomplishes work by moving the carriage along the coaster track. The carriage will move as long as it still has energy. Friction will eventually stop the carriage, but to stop the motion more quickly, many modern roller coasters use a pneumatic braking system to bring the carriage to a stop. This is why you may hear a loud air noise at the end of the ride. This noise is the pneumatic brakes being engaged through an electromagnetic system that operates the brakes when the ride is complete. The roller coaster uses a number of mechanical devices to create motion and an enjoyable experience.

Mechanical Power Systems

The field of mechanical engineering relies on the principles described above as a foundation, but there is much more to the field of mechanical engineering than scientific principles. These principles are applied to the design and creation of machines to make our lives easier. Mechanical engineers create machines that transmit power using one of two types of power systems: mechanical power systems and fluid power systems.

Mechanical power systems transmit power through direct connection with mechanical components. Mechanical power systems use a number of components, including gears, pulleys, and belts, to transmit power. In the design of mechanical power systems, mechanical engineers rely on principles of simple machines and mechanical control devices. The use of these components allows engineers to design machines that can change the amount or direction of force and the type of output motion. One example of a mechanical power system is an offset printing machine, **Figure 10-10**.

Mechanical power systems have a wide range of uses. The most fundamental is the engine. An engine that powers a vehicle is an example of a number of mechanisms working together to transmit power.

Fluid power systems transmit power by using the power of confined fluids. These systems are often used in industrial situations and can generate a large amount of force.

Figure 10-10.

This offset printing machine is an example of a product that uses mechanisms and mechanical power to operate.

jules2000/Shutterstock.com

See **Figure 10-11**. Fluid power systems generally have fewer moving parts and are easier to manipulate than mechanical power systems. Fluid power is a reliable, efficient, safe, and accurate method of power transmission.

There are two main types of fluid power systems that are categorized by the fluid used within them. ***Hydraulic systems*** use a liquid, such as water or oil, to transmit power. ***Pneumatic systems*** use air, instead of fluid, to transmit power. You can find hydraulic and pneumatic power systems in automobile brakes and airplane landing gear, farm and construction equipment, production lines, hand tools, space equipment, and even in amusement park rides. There are advantages and specific uses for both hydraulic and pneumatic power.

Hydraulic power is best used when a large amount of force is required, because liquids are not as compressible as gases. Hydraulic power is capable of providing a large amount of force and torque with a relatively small output device. Hydraulic systems are also more accurate and precise than pneumatic systems.

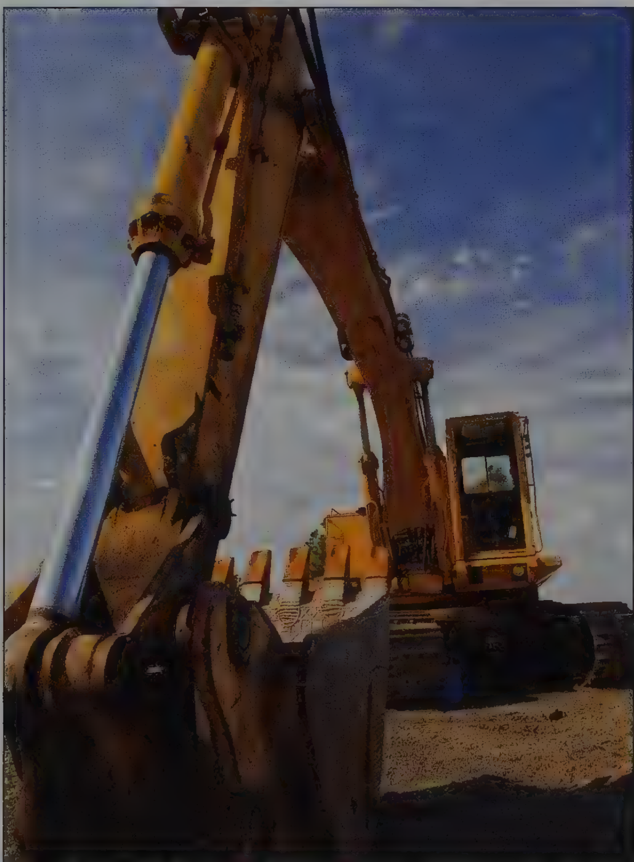

Figure 10-11.

Construction equipment, such as this backhoe, uses fluid power to transmit power.

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Pneumatic systems, however, can operate at higher speeds than hydraulic systems. Pneumatic systems use air, which is obtainable from the atmosphere, and can be released back into the atmosphere after its use. Pneumatic systems also present no spark or fire hazard, making them the desired power system in hazardous areas, such as chemical plants and mines.

The transmission of power using either mechanical or fluid power requires several key components that work together in a system. Both mechanical and fluid power systems require a power source, transmission and control devices, and output devices. This section of the chapter examines the components and applications of these two types of power systems.

Power Sources

All mechanical power systems require a source of power at the start of the system. In mechanical systems, the power source is often either chemical or mechanical energy. For example, an automobile engine uses the chemical ignition of fuel to power the piston. The movement of the piston is the initial stage of the power system. Other mechanical power systems use mechanical energy as a power source. This energy can be supplied by a person or by other sources. A bicycle requires the rider to provide the initial mechanical energy into the system. A kitchen hand mixer is a mechanical device that uses an electric motor to provide the initial mechanical energy.

In fluid power systems, the fluid must be put under pressure before the system can be used. Hydraulic systems use ***fluid pumps*** to compress fluids, and pneumatic systems use ***air compressors*** to produce compressed gas. There are several types of pumps and compressors, including gear, vane, and piston pumps, as well as centrifugal compressors. These devices use different methods to increase the pressure of the fluids or gases. The pumps and compressors

require a power source to operate. The power sources are typically gasoline or diesel engines or electric motors. The engines and motors provide the power that turns the pump. For example, a typical garage air compressor has an electric motor that is used to turn a piston crankshaft in a piston compressor. See **Figure 10-12**.

Transmission and Control Devices

Once the mechanical energy has started the mechanical power system, or the pumps and compressors have pressurized the fluid power system, the power system is used to transmit power using transmission and control devices. A number of devices and mechanisms are used to either increase speed or force, to change direction of the force, or to stop the transmission of power. Common devices in mechanical power systems include gears, belts, chains, shafts, clutches, and linkages. Pipes, tubes, hoses, and valves are the most typical fluid power control devices.

Gears are used to provide a mechanical advantage in many different machines. ***Gears*** are devices that transmit rotational force against another gear or device. Gears use a wheel and axle as a foundation, but they include linkages, which look like teeth, on the wheel, allowing them to connect to other gears or devices. By using different sizes and types of gears, you can alter the gear ratio to change the speed, torque, or direction of a power source. See **Figure 10-13**.

Figure 10-13.

These gears are spur gears of various sizes.

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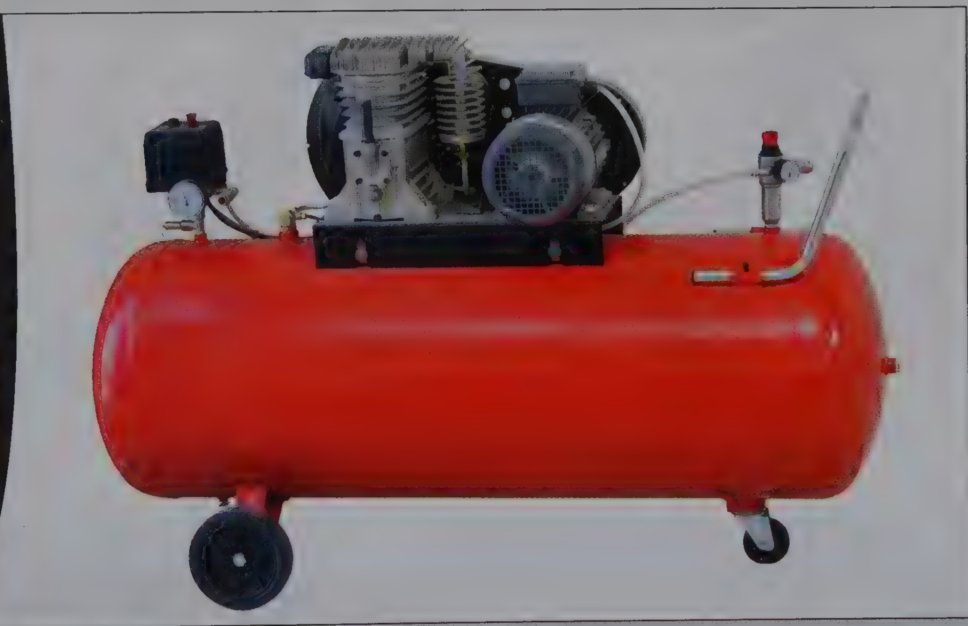

Figure 10-12.

The motor on top of this air compressor compresses the air within the tank so it can be used in fluid power applications.

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Design

Fluid Power System Schematics

The design of fluid power systems can become very complicated. Typical systems are much too complicated to discuss with other engineers and technicians, without a graphic representation. Schematics are often used to depict a fluid power system on paper. Schematics are graphic representations of the elements of a system. The most common type of schematic used in fluid power systems are circuit diagrams. Mechanical engineers use circuit diagrams to show how the fluid power components are connected and how the fluid is designed to flow through the system. The fluid power industry has a series of standard symbols for all fluid power components, so all engineers will understand the circuit diagrams.

There are several rules that are followed when engineers create circuit diagrams. The first is that the power source is on the bottom of the diagram and the output device is on the top. Between the two components are the control and auxiliary devices. The transmission lines are drawn as straight lines, even if they are to be bent or flexible in the installation of the system. The diagram depicts the connections, and not necessarily the final layout or scale. The components are typically drawn horizontally and in their initial starting position. The symbols for the components that were discussed in this chapter can be found in **Figure A**. An example fluid power system schematic is shown in **Figure B**.

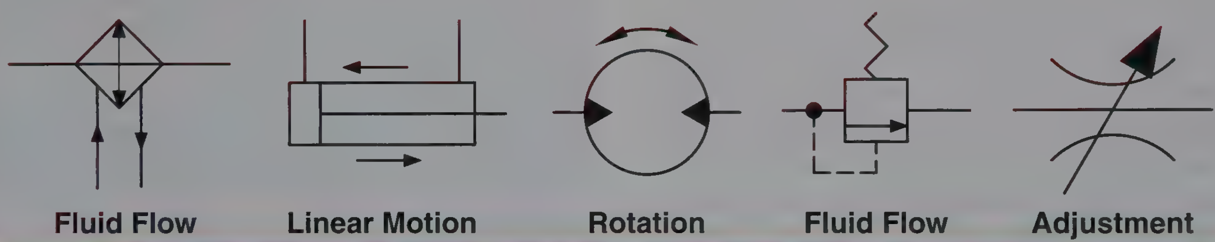

Figure A.

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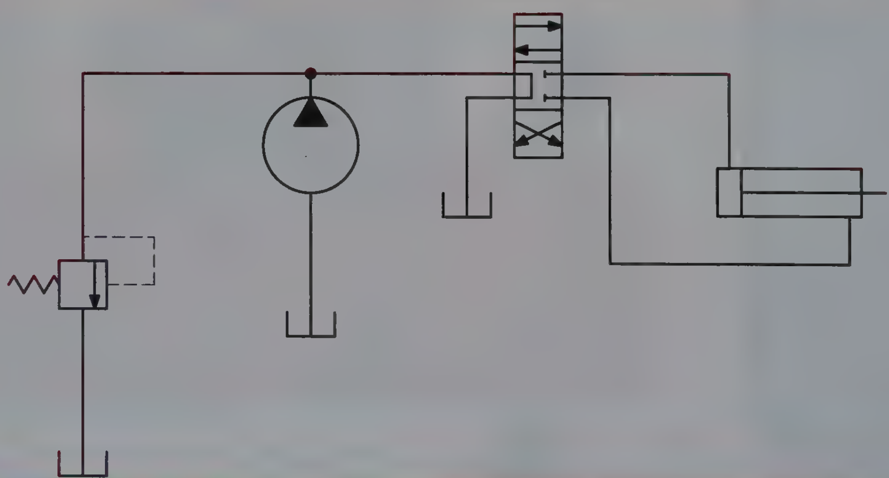

Figure B.

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A combination of pulleys and belts can help transfer power and provide mechanical advantage. Pulleys and belts are used in many machines. A ***belt*** is a band of material that is used to link and transmit energy between pulleys. Under the hood of a car, the engine powers pulleys and belts that operate different machines. Mechanical engineers use different arrangements of pulleys and belts in the car to increase speed, change the direction of power or increase torque, depending on the device they are powering from the main engine. See **Figure 10-14**.

Similar to pulleys and belts, chains and sprockets use the wheel to provide mechanical advantage. Have you ever looked at the drive system of your bicycle? Your bicycle uses a chain and sprocket system to transfer power from your pedals to the back wheel of your bicycle. By connecting a chain to the crank of your bicycle, the system is able to transfer power to different size sprockets to control the amount of force needed to move your bicycle. If you have ridden a mountain bike with 10 speeds, you have felt the mechanical advantage that different-sized sprockets provide. As you shift through the different speeds, each sprocket changes the amount of force needed to turn the back wheel of your bike.

Clutches are a tool that connects a power source to other parts of the machine. Clutches are most frequently used to connect two rotational devices. For example, the engine of your car and the drive train that moves the car are connected by a clutch. In a car, the clutch is needed because the engine is always rotating, but you may not want the vehicle to be moving. Also, clutches allow you to change gears to adjust the mechanical advantage of the engine to transfer power to the rest of the vehicle.

Linkages are often used to transfer energy from one power source to another. Linkages are rigid components that have a series of joints that are combined to create a closed chain, **Figure 10-15**. One common example of linkages is locking pliers. Linkages are often used to adjust a range of motion.

In fluid power systems, fluid lines are used to transmit the fluid throughout the system. Common fluid lines are pipes, tubes, and hoses. The type of lines used is carefully selected depending on the type of fluid, the amount of pressure, the system temperature, and other factors. Depending on these factors, the system may use rigid steel pipe, copper or plastic tubing, or synthetic or rubber hoses. Each material and

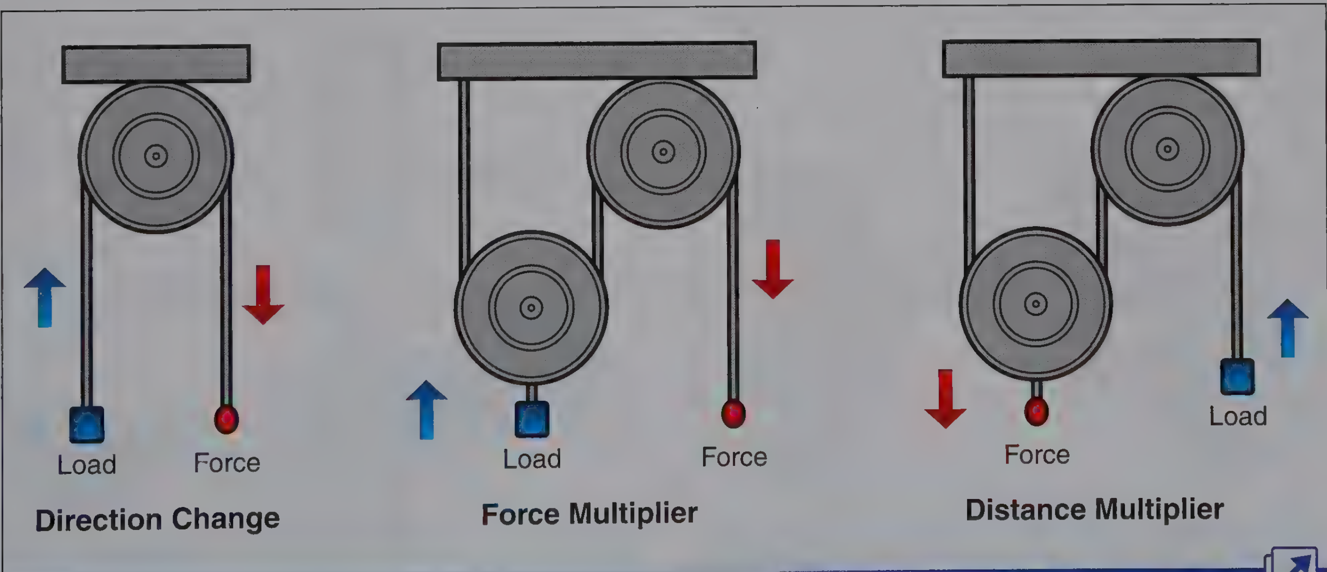

Figure 10-14.

Pulleys can be used to change direction, force, or distance.

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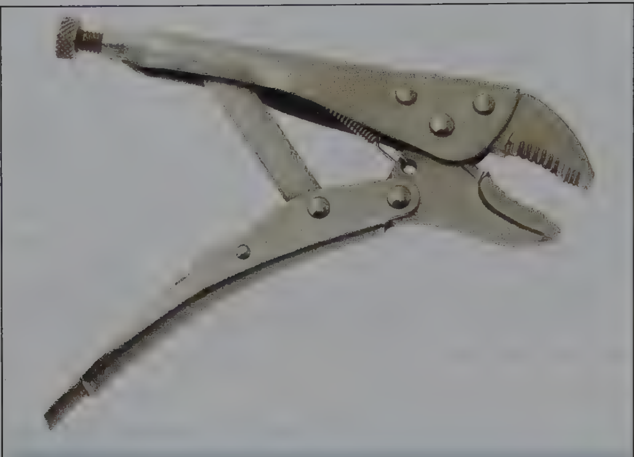

Figure 10-15.

Linkages allow a change in direction, force, or type of motion.

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type of line has specific advantages and disadvantages that must be considered.

The flow of the fluid is controlled by valves. ***Valves*** can be used to control either the rate or direction of the fluid flow, **Figure 10-16**. Valves that control the rate of flow operate by either closing or restricting the path of the fluid. Flow control valves have an input and output side with some type of device in the center to change the rate of flow. A needle valve, for example, has a small cone-shaped stem that is seated into a small orifice in the valve. The closer the end of the needle is to the orifice, the more the flow is restricted.

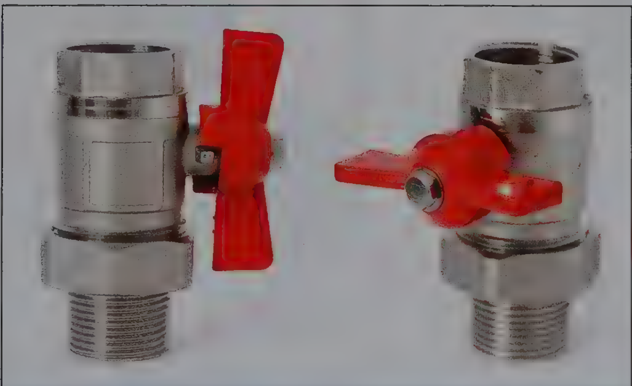

Figure 10-16.

Valves are used to restrict or change the flow of fluid. These shut-off valves are a common example. Water faucets are also fluid valves.

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In many situations, the flow of fluid does not need to be altered, but the direction does. Directional control valves are used to control where the fluid is sent within the system. The simplest directional control valve is a three-way valve, **Figure 10-17**. A three-way valve is often used with a push-button control for a single fluid power device, such as a log splitter. In a pneumatic system, for example, when the valve is depressed, air is sent to the cylinder. When the valve is released, the air is allowed to leave the cylinder and escape through the exhaust port. Another common type of directional control valve is a four-way valve. Four-way valves allow for a change in direction of a fluid. See **Figure 10-18**. They are most often used with double-acting cylinders, which are discussed later in this chapter.

All the valves used in fluid power systems can be operated in several ways. The simplest form of valve operation is manual control in the form of push buttons, hand levers, and foot pedals. For example, in a backhoe, the operator uses hand controls (valves) to raise and lower the shovel. However, valves can also be controlled mechanically, with the use of mechanisms described earlier in the chapter, or electronically,

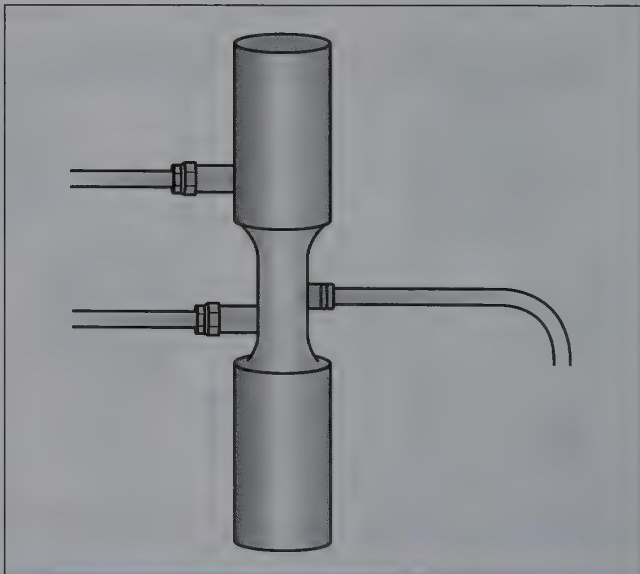

Figure 10-17.

Three-way valves allow for a change in direction.

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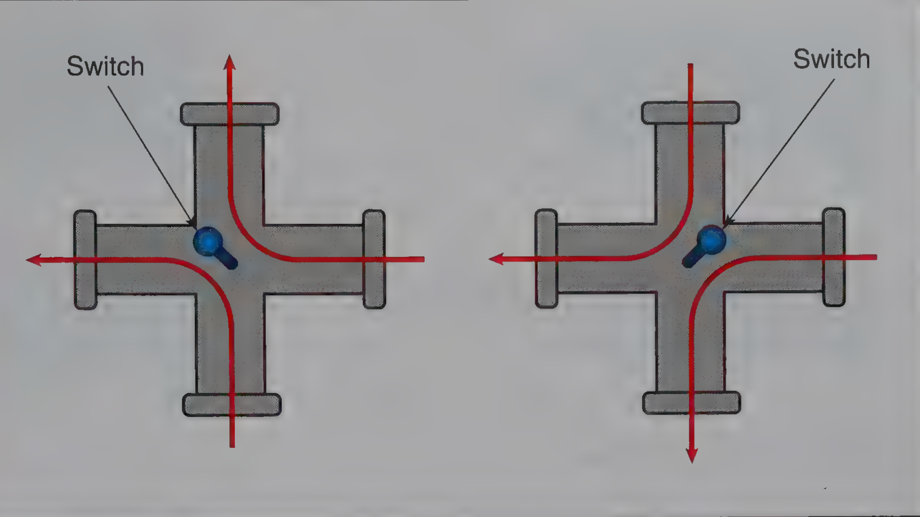
Figure 10-18.
Four-way valves allow for changes in direction and are commonly used with double-acting cylinders.



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using sensors or solenoids. In a production line, solenoids may be used to operate a valve that controls a pneumatic stamping machine.

Output Devices

The goal of any power system is to produce usable motion. The usable motion can be any of the six types of motion described earlier, but is often either rotary or linear. In fluid power systems, ***actuators*** convert fluid power into either linear or rotary motion.

When linear motion is the desired outcome of a fluid power system, actuators known as cylinders are used. ***Cylinders*** are devices that use the pressure of fluid to move a piston that is connected to a rod. See **Figure 10-19**. Cylinders are simple devices with only a few parts. They have a cylinder body that has a round internal chamber with caps on each end. A piston, rod, and several seals maintain the pressure inside the chamber. These devices also have ports that allow the fluid to enter and exit the cylinders. The fluid enters the cylinder and pushes on the piston, which causes the piston and rod to move. The movement of the rod is the linear output motion of the system.

The simplest cylinder is a single-acting cylinder. These have one port for the fluid to flow in and out. Once the piston and rod are extended, there must be a second force that retracts the cylinder. See **Figure 10-20**. In most cases, the force is provided by an internal spring. In other devices, like a hydraulic jack, the weight of the object and/or gravity is used to retract the cylinder. In situations that need a more controlled or forceful return of the cylinder, a double-acting cylinder is used. Double-acting cylinders have two fluid ports, one on each side of the piston. Fluid enters one port to extend the rod and the other port to retract the rod.

When rotary motion is the desired output of a mechanical system, a combination of shafts and bearings are often used in machines. ***Shafts*** are cylindrical pieces used to transfer rotary motion. Shafts can be connected to gears, pulleys, and wheels. While shafts are a common output device, they can also be used as an input device. In those situations, the shafts are known as driven shafts. To help shafts gain a mechanical advantage,

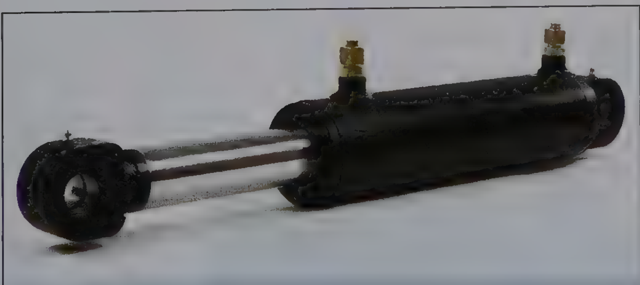

Figure 10-19.
Cylinders, such as this one, are often the output device in a fluid power system.

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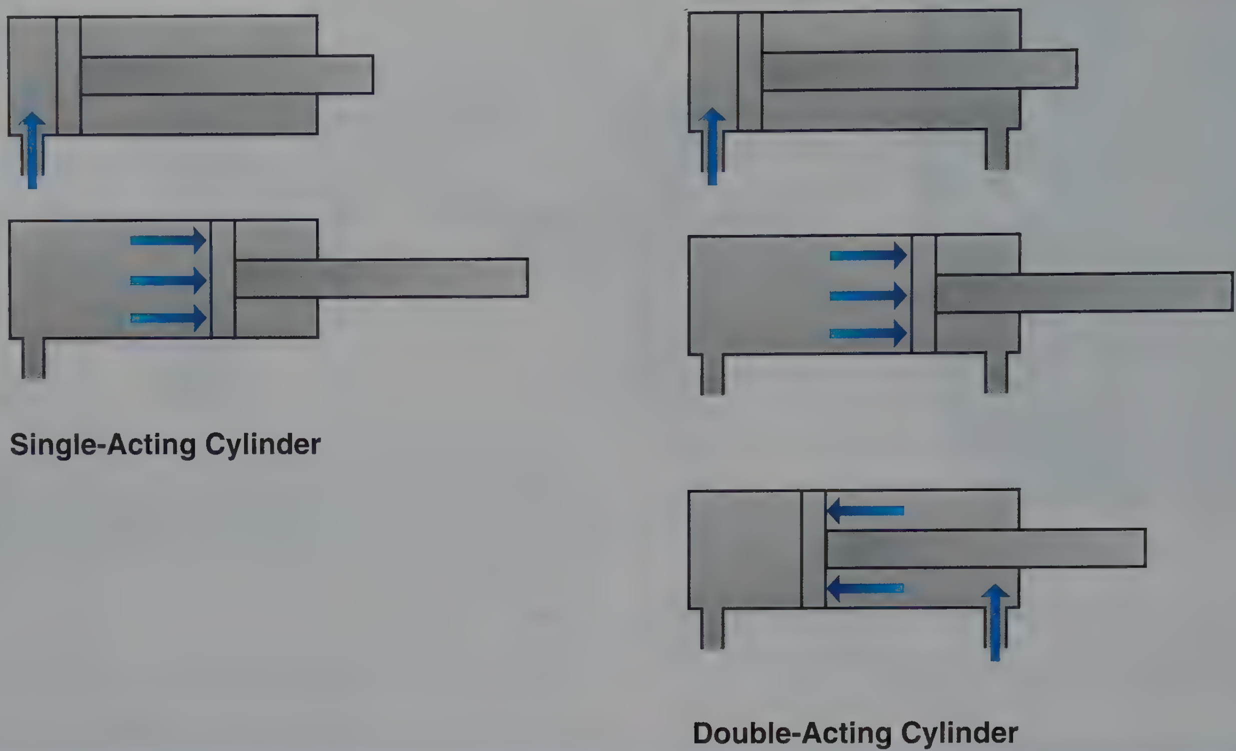

Figure 10-20.

In single-acting cylinders, the fluid only pushes the cylinder in one direction. In double-acting cylinders, fluid can be used to extend or retract the cylinder shaft.

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bearings are used to transfer the energy from the shaft to the wheel. ***Bearings*** are metal pieces that are used to reduce friction with shafts by using smooth metal balls inside circular pieces of metal that fit around the shaft. This reduces friction by allowing controlled movement to the output connection of the shaft.

In fluid power systems, several types of actuators can be used as a rotary output device. ***Rotary actuators*** are devices that can provide a small amount of rotation. They look similar to cylinders, but have different internal workings to create rotary motion. See **Figure 10-21**. These devices are often used to move or adjust

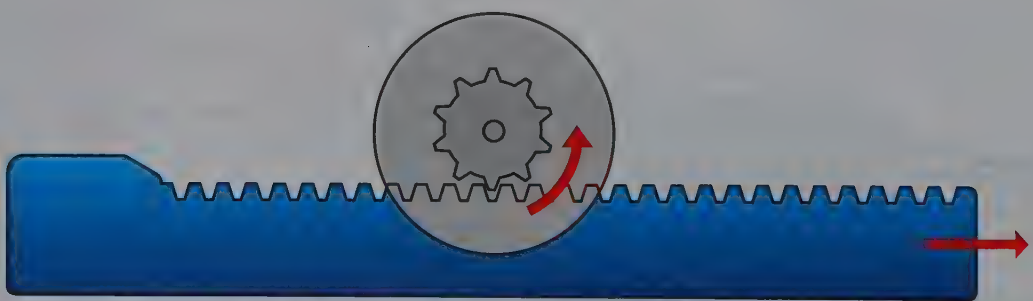

Figure 10-21.

Expand learning

A rotary actuator changes the direction of motion from linear to rotary, or vice versa.

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products on a production line. If a large amount or continuous rotation is needed, a fluid motor may be used instead of a rotary actuator. ***Fluid motors*** are the same as fluid pumps, only used in reverse. For example, a gear pump provides fluid power if a power source turns the gears and fluid is pumped through the gears. However, the opposite is also true. If you pump fluid through the gears, the power of the fluid will turn the gears and the gear shaft. The turning gear shaft is rotary motion. Pneumatic fluid motors are often used in air tools and hydraulic fluid motors can be used in hydrostatic drive situations to move heavy machinery.

Mechanical Power Principles and Formulas

The proper application of mechanical principles and tools is critical when designing mechanical systems, so analysis is needed to select the best way to accomplish tasks. The goal of mechanical engineers is to make work easier. To determine if work is made easier or to plan and develop machines, engineers use mathematical calculations of many principles to compare benefits of specific designs and to identify potential disadvantages of designs.

Work

As previously discussed, the concepts of force and work are critical to our understanding of how engineers measure and design mechanical systems. The amount of force used to move an object is critical in measuring the amount of work produced by a system. For example, when we use the formula of work = distance × force, we can determine that if we use 300 lb of force to move an object 10′, we have accomplished 3000 ft-lb of work.

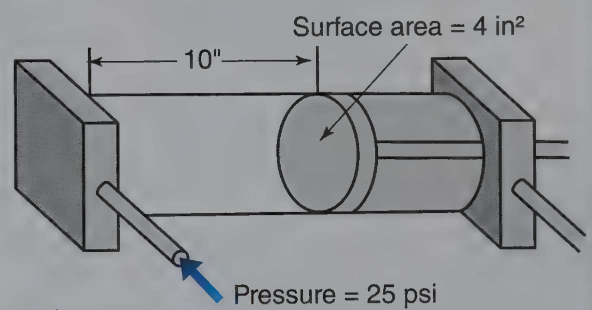
In fluid power systems, work is calculated using pressure (p) and the volume of fluid that is displaced (ΔV). The formula is $w = p \times \Delta V$. The displaced volume (ΔV) of a cylinder is calculated by multiplying the area of the piston and the length that it moves (ΔV = Area × Length). The entire formula reads as $w = p \times (A \times L)$.

For example, imagine that you have a cylinder with a piston surface area of 4 in^2 that can travel 10″ in a system that can deliver 25 pounds per square inch (psi) of pressure. The cylinder in that example can apply 1000 in-lb of work. See **Figure 10-22**.

Pressure

Pressure is fundamental to understanding fluid power. Pressure is the amount of force acting on each unit of surface area. It is calculated by dividing surface area, in inches, by the amount of force, in pounds, to determine the pounds per square inch (psi). It is expressed as $p = f / a$. ***Pascal's law*** states that all fluids exert the same amount of pressure in all directions when in a limited space. This means that the pressure of a fluid should be the same at every point in a fluid power system.

The principle of pressure can be seen in a simple example of a hydraulic jack. A hydraulic jack is two cylinders connected together.



Calculate ΔV:

$$\Delta V = \text{Area} \times \text{Length}$$
$$\Delta V = 4\text{ in}^2 \times 10\text{ in}$$
$$\Delta V = 40\text{ in}^3$$

Calculate Work:

$$w = p \times \Delta V$$
$$w = 25\text{ lb/in}^2 \times 40\text{ in}^3$$
$$w = 1000\text{ in-lb}$$

Figure 10-22.
The amount of work applied by the cylinder can be calculated.

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As the handle of the jack is depressed, fluid is pumped out of the input cylinder and into the output cylinder. The input cylinder is much smaller than the output cylinder.

For example, imagine the input cylinder is 2 in^2 and the output cylinder is 4 in^2. As you pump the handle of the jack, 150 lb of force are exerted on the input cylinder. To find the pressure, divide the force by the size of the input cylinder:

$$\frac{150 \text{ lb of force}}{2 \text{ in}^2} = 75 \text{ psi}$$

The pressure of 75 psi is transferred to the other piston. To calculate the force, multiply the pressure by the size of the output cylinder:

$$75 \text{ psi} \times 4 \text{ in}^2 = 300 \text{ lb}$$

This example shows mechanical advantage in a fluid power system. See **Figure 10-23.**

However, as discussed previously, there is a trade-off. The advantage found in force would be inversely proportional to the distance travelled. So, because the force doubled in the example, the distance is halved. If the input cylinder travelled two inches to exert the pressure, the output cylinder only moved one inch. In a fluid power system, the equation for pressure ($p = f / a$) is set up to calculate the required cylinder pressure. However, the same formula can also be used to find the cylinder force ($f = p \times a$) and the desired piston area for a cylinder ($a = f / p$).

The pressure in a fluid power system is controlled both by the type of pump or compressor and the regulators that are used. All pumps and compressors have a maximum amount of pressure they can generate. For example, a common portable air compressor can generate a maximum air pressure of 160 psi. The fluid pump on a backhoe may have a rating of over 3000 psi, and industrial pumps may have a maximum pressure of 15,000 psi. As a comparison, a typical fire hose is operated at around 250 psi.

Power

Another important concept is power. Think of the last vehicle you rode in—do you know how much power it has? You may know the speed you are traveling in a car by looking at a speedometer, but you probably do not know how much power it took to make the car move. Power is the rate at which work is performed. We measure power using the formula of power = work / time in seconds ($p = w / t$). Power can be measured in both mechanical and fluid power systems.

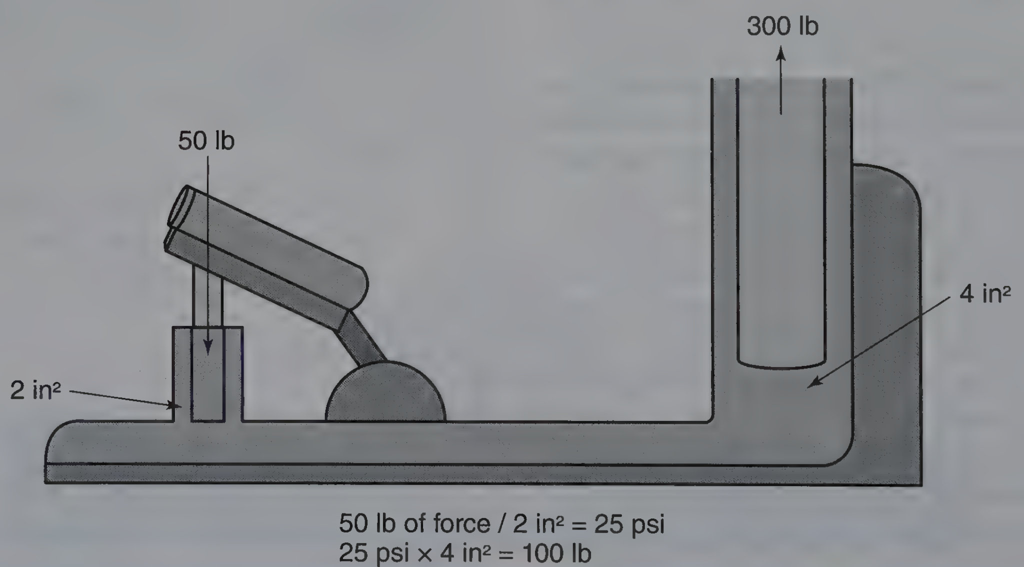

Figure 10-23.

Pressure in a fluid system can be calculated.

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For example, imagine you move a 500-lb refrigerator 10′ in 20 seconds. The formula is:

$$p = \frac{w}{t}$$

$$p = \frac{500 \text{ lb} \times 10'}{20 \text{ seconds}}$$

$$p = \frac{5000 \text{ ft-lb}}{20 \text{ seconds}}$$

$$p = \frac{250 \text{ ft-lb}}{\text{second}}$$

In a fluid power system, for a cylinder that applies 800 in-lb of work in 2 seconds, the power would be 400 in-lb per second.

In devices that generate large amounts of power, horsepower is used to measure the amount of power produced. ***Horsepower*** is a unit of work defined as 33,000 foot-lb/min. To calculate horsepower, we use the formula: hp = work / (time in minutes × 33,000). We can use horsepower to measure the power produced by various systems. You can even calculate your own horsepower. Imagine there is a 200 lb box that you need to move 25′. Assume it took you two minutes to move it.

$$\text{hp} = \text{weight} \times \text{distance} / \text{time} \times 33{,}000$$

$$\text{hp} = 200 \text{ lb} \times 25' / (2 \text{ minutes} \times 33{,}000)$$

$$\text{hp} = 5000 \text{ ft-lb} / 66{,}000 \text{ minutes}$$

$$\text{hp} = 0.075 \text{ hp}$$

Torque

Power used to describe the rate at which work is performed in a linear direction, but we use torque to describe rotational force. ***Torque*** is the measure of how much force acting on an object causes that object to rotate. Torque is usually measured in foot-pounds and can be used to determine the rotational power of a machine. In a mechanical system, torque is calculated by multiplying the distance from the center of the force by the amount of weight moved by the motion. Thus, the formula used is torque = force × radius. For example, torque is used when you turn a nut with a wrench. If you are using a wrench that is 1′ long (radius of the motion) and you use 60 lb of force, you generate a torque of 60 ft-lb. Torque can be used to determine the rotational horsepower of a machine. To calculate horsepower, you must know the revolutions per minute (rpm) of a machine. The formula for rotary mechanical power measured in hp is torque (force × radius) × (rpm/5252). See **Figure 10-24**. In the previous example of using a wrench that generates 60 ft-lb of torque, if you were to turn the wrench 10 times per minute, you would generate 0.114 hp.

$$\text{rotational hp} = \frac{\text{Torque} \times \text{rpm}}{5252}$$

$$\text{rotational hp} = \frac{60 \text{ ft-lb} \times 10 \text{ rpm}}{5252}$$

$$\text{rotational hp} = \frac{60}{5252}$$

$$\text{rotational hp} = 0.114$$

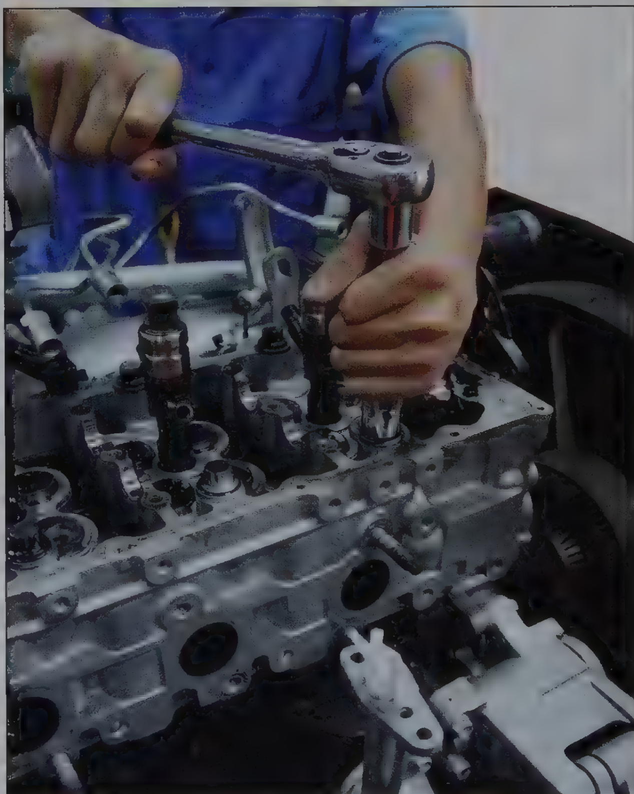

Figure 10-24.

The power that is being transmitted in this image is known as torque.

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In a fluid power system, torque is calculated using the following formula:

$$\text{torque } (t) = \frac{\text{pressure } (p) \times \text{motor displacement}}{2\pi}$$

Motor displacement is the amount of fluid that is pushed out of a fluid motor each time the gears make one revolution. For example, calculate the torque of an industrial hydraulic motor that has a displacement of 5 in^3 and operates at 3500 psi:

$$t = \frac{p \times \text{motor displacement}}{2\pi}$$

$$t = \frac{3500 \text{ psi} \times 5 \text{ in}^3}{2\pi}$$

$$t = 2785 \text{ in-lb}$$

Gear Ratios

Mechanical engineers must direct the correct amount of power through the system to achieve their intended horsepower. Gear ratios are used to ensure the proper amount and speed of force is applied to parts of mechanical systems. A ***gear ratio*** is the relationship between two gears that describes the change in torque. Gear ratios are described by the relationship between the input shaft (drive gear) and output shaft (driven gear).

To find the gear ratio for two gears, you must compare the circumference of the gears used. To calculate the ratio, we use the formula gear ratio = (diameter of smaller circle × π) / (diameter of bigger circle × π). Because the number of teeth on a gear is also proportional to its circumference, the ratio can also be calculated using the number of teeth on the gear. For example, in a set of two

Tools

Micrometers

Selecting the correct gears, pulleys, shafts and linkages requires careful measurements. Mechanical engineers use accurate tools that can measure mechanical components. These tools provide precise measurements and are designed for a specific use.

Engineers use micrometers to measure the outside size of different objects, **Figure A**. To understand how to use a micrometer, first we must understand the different parts of the tool. The micrometer uses two measuring rods, the body of the micrometer, a barrel and the thimble. To use the micrometer for measurements, you must twist the thimble on the barrel until both measuring rods are in contact with the object you intend to measure. Once you have contact with the object, you must read the number on the barrel and add it to the number on the thimble. The barrel represents the hundredths of an inch and the thimble represents up to one thousandth of an inch. You must also read and measure the number of marks that follow the number on the barrel. Each mark is equal to 0.025″. That number is added to the barrel and thimble numbers. To further explain, follow the example and diagram in **Figure B**.

Figure A.

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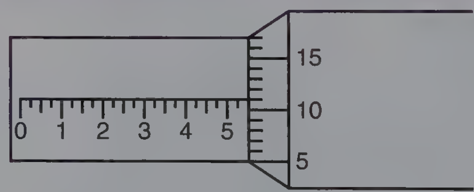

Step 1: Read the barrel = 0.5"
Step 2: Read the marks = 1 mark = 0.025"
Step 3: Read the thimble = 0.011"
Step 4: Add together = 0.5" + 0.025" + 0.011" = 0.536"

Figure B.

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meshing gears, if one had 36 teeth and the other had 12 teeth, it would have a gear ratio of 3:1. With this ratio, the input shaft would spin three times for every one revolution of the output shaft. In ratios where the driver gear is larger (like 3:1), the output shaft is slowed down and provides more torque. When gears increase speed, the torque lessens (like in a 1:3 ratio), just as when the gears are slowed down, the torque increases. Mechanical engineers use different gears that provide various ratios to transfer power through systems at different levels of torque and speed.

Efficiency

With all of the mechanical principles, there can be a difference between the calculated measurement and the actual measurement. Engineers use a formula that investigates the relationship between the ideal mechanical advantage (IMA) and the actual mechanical advantage (AMA). IMA is how efficient the machine will be in an ideal situation and AMA is the "real world" efficiency by including the impact of the outside force of friction. Both formulas use the mechanical advantage of output force divided by input force for their calculations, but AMA uses actual measurements from testing the machine. IMA calculations are done to figure the potential mechanical advantage of a machine, while AMA calculations must be done by measuring the actual input force divided by the actual output force.

For example, let's say you are moving a 200-lb box onto a trailer that is 10′ in the air. If you use a 20′ ramp, you will divide the input distance by the output distance and have a mechanical advantage of 2:1. So, ideally it should take 100 lb to move the 200-lb box using the ramp. This IMA calculation does not include the friction you get from pushing the box on the ramp. In reality, it may take 110 lb of force to move the box because of friction which reduces the mechanical advantage. We can determine the efficiency of the machine by comparing the IMA with the AMA. If we use the same box, we can calculate the efficiency using the following model:

$$\text{IMA} = \frac{\text{Load}}{\text{Ideal Effort}}$$

$$\text{IMA} = \frac{200\text{ lb}}{100\text{ lb}}$$

$$\text{IMA} = 2.0\text{ IMA}$$

$$\text{AMA} = \frac{\text{Load}}{\text{Actual Effort}}$$

$$\text{AMA} = \frac{200\text{ lb}}{110\text{ lb}}$$

$$\text{AMA} = 1.82\text{ AMA}$$

We then must divide the AMA by the IMA to determine the system efficiency:

$$\text{Efficiency} = \frac{1.82}{2.0 \times 100}$$

$$\text{Efficiency} = 91\%$$

Efficiency is important to mechanical engineers because they want to develop systems that do not waste energy when accomplishing work, but they must also consider the way energy is transferred inside the system. To measure the amount of power they receive from the system they must consider gear ratios, horsepower, and torque as ways to adjust and measure the output power desired.

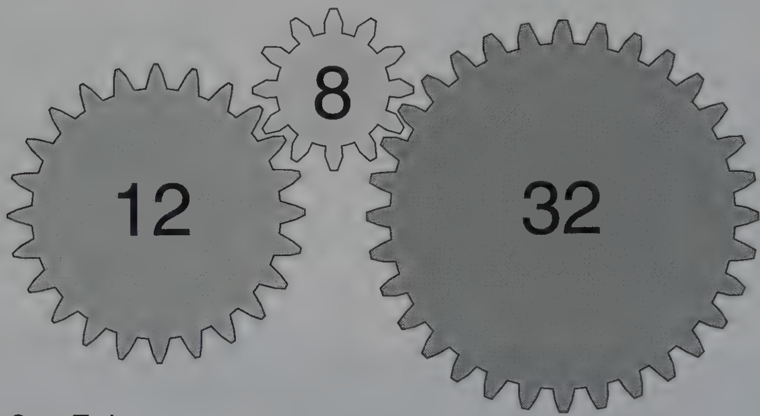
Mechanical Engineering Applications

The usefulness of all of the principles, applications, and calculations discussed in this chapter are found when they are applied to solve real problems or used to create practical devices. The applications can be simple or very complex, relying on using combinations of all the different topics discussed to design efficient and effective machines. Examples of mechanical engineering applications include gearboxes, air brakes, backhoes, and automobiles.

Gearboxes

Gearboxes are a common mechanical device used to change the torque, direction, or speed of a rotating shaft. Gearboxes have a number of uses, such as wind turbines, farm equipment, washing machines, and many industrial applications.

Most often the gearbox slows down the speed of the shaft, which increases the amount of torque. Gearboxes have input and output shafts that are connected by a series of gears. The series of gears is known as a gear train. A gear train in which all of the gears are linked together in a row is known as a simple gear train. When pairs of gears are connected to each other on a common shaft, it is known as a compound gear train. Gear ratios can be found for each type of gear train, **Figure 10-25**. Gearboxes are designed to have one gear ratio. However, it is often desirable to be able to change the gear ratio of a gearbox. This is the case in the use of automobile transmissions. Manual and automatic transmissions that are used in automobiles are essentially complex gear boxes that allow for a change in the gear ratio.

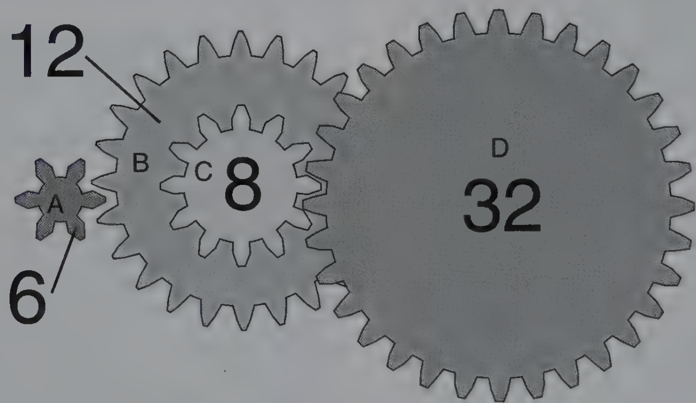


Gear Train

Gear Ratio = # of teeth on driver / # of teeth on follower

Gear Ratio = 12 / 32

Gear Ratio = 3 / 8 or 1:2.66



Compound Gear Train

$$\text{Gear Ratio} = \frac{\text{\# of teeth on "B"}}{\text{\# of teeth on "A"}} \times \frac{\text{\# of teeth on "D"}}{\text{\# of teeth on "C"}}$$

$$\text{Gear Ratio} = \frac{12}{6} \times \frac{32}{8} = \frac{8}{1} = 8:1$$

Figure 10-25.

Gear ratios can be calculated using simple formulas.

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History of Power Sources

Over the course of history, humans have created mechanical power systems that have utilized a number of power sources. Prior to the Industrial Revolution, humans, animals, and natural forces were used in the generation of energy for use in power systems. Each of the power sources had advantages and disadvantages. Humans could power small systems and devices. Looms used in textiles were human powered. However, humans tire and can only work for a limited amount of time on a daily basis. Animals were used for several purposes, including turning axles that powered grain mills. Animals are fairly inefficient and must be fed and cared for, creating an added expense.

Natural forces, such as the wind and water, were used as alternatives to humans and animals. Wind was harnessed as a power source possibly as early as the tenth century. Wind power has been used all over the world to provide the power needed to pump water from underground wells. Using the wind as a direct power source has the disadvantage of unpredictability. The most widely used natural power source prior to the Industrial Revolution was the use of flowing water. Waterwheels were used to power grain and saw mills, textile shops, and other production facilities. Water was more consistent and constant than wind, but required a water source at the mill or facility.

These sources (humans, animals, wind, and water) were used exclusively to generate power until the creation and refinement of the steam engine during the Industrial Revolution. As the steam engine became a reliable power source, the use of the previous sources declined. Today, gasoline and diesel engines and electric motors have replaced the steam engine. However, the original power source powered mechanical devices and systems for thousands of years before the Industrial Revolution.

Air Brakes

Another example of a pneumatic system is an air brake system on a large truck. Large vehicles often use fluid power braking systems because of the large amount of force they can provide. In an air brake system, the vehicle's engine is connected to an air compressor by a pulley. The compressor sends air into large storage tanks, one for each wheel. The driver's foot pedal is a control valve and when it is activated, the compressed air from the storage tank engages a cylinder at each of the brakes. Through mechanical linkages, the cylinder transmits its power into a braking force.

Backhoes

Hydraulics is common on heavy machinery. Construction and farm equipment, for example, often rely on hydraulic power to operate the devices and, in many cases, to move the vehicle. In construction, machines such as loaders use hydraulic power for both linear and rotary motion. Hydraulic cylinders are used to provide the force required to lift bucket loads of soil. In a backhoe attachment, several cylinders are used to generate articulated movement, much like a human arm. Hydraulics is also used to power fluid motors that generate rotary motion in tools such as augers, brooms, and snow blowers and to power the fluid motors that turn the drive wheels of the machine.

This fluid power is generated in a pump that is driven by a diesel engine. The pressurized fluid is then sent to the various cylinders and fluid motors. The operator controls the output devices with the use of hand levers (or joysticks) and foot pedals that serve as valves. See **Figure 10-26**.

In application, fluid power systems often are combined with simple machines and mechanisms to create usable motion. For example, in a backhoe the hydraulic cylinder is used to raise and lower the arm of the backhoe. In that situation, the backhoe arm is a third-class lever and the cylinder is providing the input force. In other situations, a cylinder may be connected to a wheel and axle to create rotary motion. This is how steam locomotives are operated.

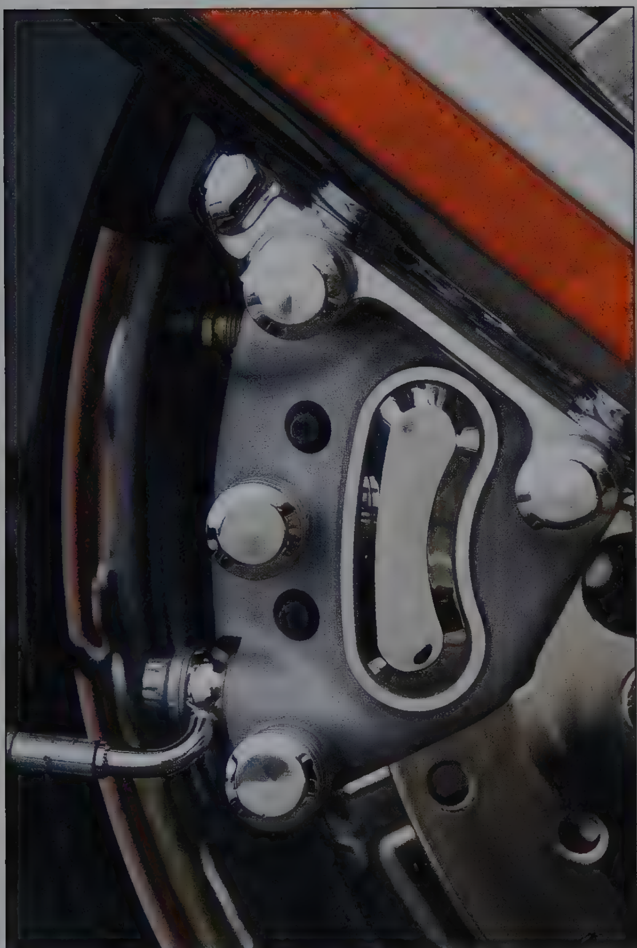

Figure 10-26.

This motorcycle brake is powered by fluid power.

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The cylinder is driven by steam, which is connected to the wheel through a series of linkages. As the piston in the cylinder moves, so do the wheels of the locomotive. In industrial situations, cylinders operate cams or gears. Fluid power and mechanical systems work together in power systems.

Automobiles

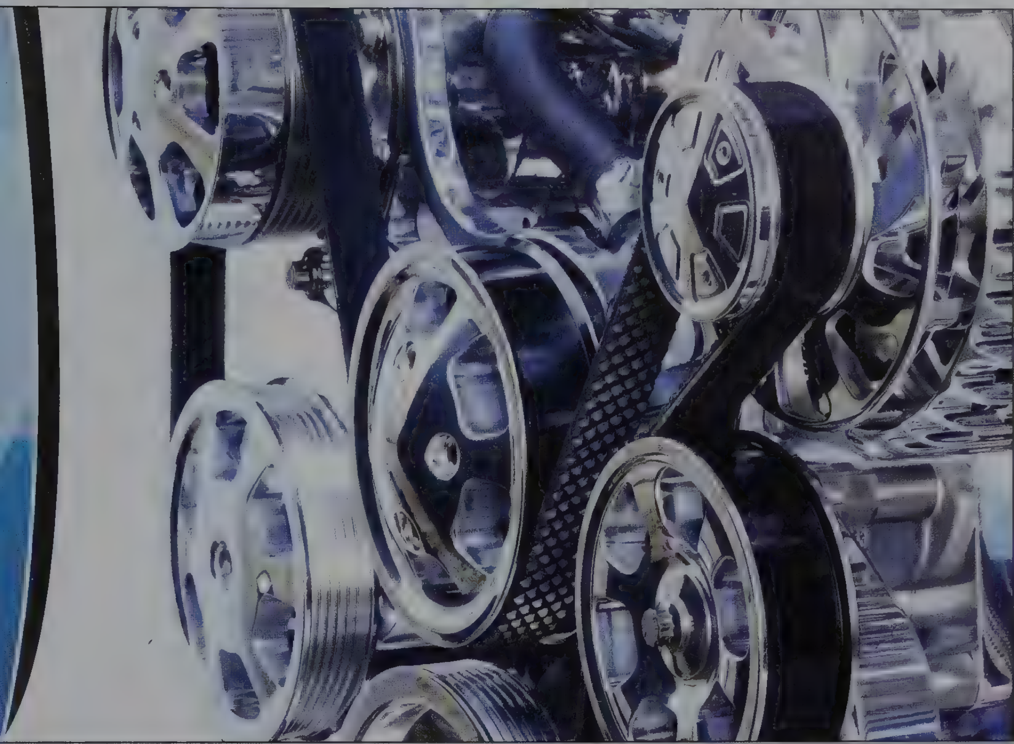
As you have read through this chapter, the automobile uses many of these principles, yet they rely on each other to successfully move a vehicle. When we first get seated in the automobile, we have the potential energy stored in the fuel and battery of the vehicle, but that energy is quickly converted to kinetic energy when we start the car. This is when we begin to use the complex mechanical systems together to move the vehicle.

The internal combustion engine uses many simple machines such as levers and wheels and axles to take the fuel and transform it into useful kinetic energy. See **Figure 10-27**. Once the engine transforms the chemical energy of the fuel into mechanical energy, this energy is transferred to different parts of the vehicle. To control the energy from the engine, we use a series of clutches and gears in the transmission to direct and control the power to the drive train. Also, there are multiple series of belts and pulleys to power devices, such as the cooling fan, alternator, and power steering pump. As this energy is transferred and converted, the vehicle becomes one machine that uses all of the different devices developed by mechanical engineers. Mechanical engineers must be able to combine different machines to produce easier ways to accomplish work.

Mechanical Engineering in Action

Mechanical engineering often focuses on the transmission of power. Over the years, mechanical engineers have designed systems to transmit power in automobiles, aircraft, and even spacecraft. These innovations have

Figure 10-27.
This automobile engine is an example of a mechanical system that uses a number of mechanisms. The pulley and wheels and axles are visible in this image.



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improved efficiency and made the travel that we know today possible. One area of power transmission in which mechanical engineers have been involved over the past several decades is the design of hybrid engine systems. A hybrid engine system is a power transmission system that uses two or more sources of power. The most common hybrid system in automobiles today is the gasoline-electric hybrid system.

A gasoline-electric hybrid system combines a traditional gasoline engine with an electric motor. There are two main ways in which gasoline-electric hybrid systems work: parallel hybrid systems and series hybrid systems.

In parallel hybrid systems, a gasoline engine and an electric motor are both connected to the transmission. The transmission sends the power from the engine or motor to the wheels. In these systems, either the gasoline engine or the electric motor can power the vehicle.

In series hybrid systems, the electric motor is the only power source for the transmission. The gasoline engine is used to either charge the batteries for the electric motor or to directly power the electric motor. The gasoline engine is never the sole power source for the transmission.

Mechanical engineers are involved in many aspects of the work on hybrid engine systems. They work to improve the efficiency and design of the traditional gasoline engine that is used in the system. They design and improve the transmission systems that receive the power and that is then transmitted to the wheels that drive the vehicle. Mechanical engineers also work with electrical engineers in the design of the electrical motors and electronic systems to ensure the mechanical and electrical systems operate well together.

Summary

- Mechanical engineers represent one of the largest engineering professions.
- The work of mechanical engineers is related to the scientific principles of force, work, and power.
- All mechanical tools need an energy source to do work.
- Mechanical engineers deal primarily with mechanical and fluid power when they are designing and developing power systems.
- Mechanical power systems use one of six different types of motion.
- The fundamental concepts of most designs developed by mechanical engineers rely on six simple machines.
- The two main types of fluid power systems are hydraulic systems and pneumatic systems.
- Mechanical engineers use mathematical calculations of principles including work, pressure, power, torque, gear ratios, and efficiency.
- Mechanical engineering applications include gearboxes, air brakes, backhoes, and automobiles.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What two types of systems are designed, built, and maintained by mechanical engineers?
2. The push or pull on an object resulting from contact with another object is _____.
3. _____ is the application of force to move an object a distance.
4. The rate at which work is performed is _____.
5. Describe the difference between potential and kinetic energy.
6. Give the definition for each of the following types of motion.
   A. Linear motion.
   B. Rotary motion.
   C. Reciprocating motion.
   D. Oscillating motion.
7. A(n) _____ is a simple machine that uses a stiff bar rested on a fulcrum, or pivot, to lift or move a load.
8. A(n) _____ is a simple machine that gains mechanical advantage by moving the object a longer distance while using less force.
9. *True or False?* Mechanical power systems use components such as gears, pulleys, and belts to transmit power.
10. _____ systems use liquid to transmit power, while _____ systems use air.
11. What are the two most common power sources in fluid power systems?
12. _____ are devices that mesh with similar devices to transmit power.

13. In a mechanical power system, a(n) _____ is a cylindrical piece used to transfer rotary motion.
14. A forklift raises a 400-lb stack of shingles 12′ in the air. How much work has been done?
15. Calculate how much force would be generated in a fluid power cylinder with an area of 0.5 in^2 operating at 120 psi.
16. Calculate the horsepower provided by the forklift, if the shingles in Question 14 are raised in 3 minutes.
17. Determine the gear ratio of a gear set in which the driver gear has 60 teeth and the driven gear has 15 teeth.
18. Calculate the ideal mechanical advantage that is provided by the following simple machine: One end of a 15′ ramp is placed on the ground and the other is placed on a loading dock that is 3′ above the ground. How much effort would be required to push a 150-lb box up the ramp?
19. Determine the efficiency of the previous machine, if it required 34 lb to push the 150-lb box up the ramp.
20. Give at least two applications of mechanical power.

Reinforce learning

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
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Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 11

Bioengineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *bioengineering*.
- Identify the five fields of study on which all bioengineering is based.
- Discuss the different forms of bioconversion used in biological engineering.
- Describe the role of bioengineering in agricultural production.
- Describe the impact of biomedical engineering on our society.

Key Terms

agricultural engineering
anaerobic digestion
artificial selection
biochemical conversion
bioengineering
biomass
biotechnology
cell
cell biology
cloning
combustion
compost
composting
crop yield
DNA fingerprinting
evolutionary biology
fermentation
gasification
gene
genetically engineered crop
genetics
herbicides
homeostasis
monoclonal antibodies
natural selection
pyrolysis
thermochemical conversion

Practice vocabulary

Few engineering disciplines have a larger impact on humans than bioengineering. Throughout history, humans have used engineering as a way to adapt the natural world to better fit their needs and wants through creating safe structures for shelter, advanced transportation methods, and manufacturing products that make life more comfortable. Bioengineers develop solutions for the aspect of quality of life. Biological, agricultural, and biomedical engineers create energy-production methods from biological matter, safer food supplies to consume, and technologies to investigate illnesses.

Bioengineering is a field that uses biological organisms and other biological tools to help humans and other species live. Bioengineering relies on the field of biology for the foundational principles of living objects and also uses the engineering design process to create solutions to problems related to the human body. Bioengineers work in many different fields. Some bioengineers work in agricultural crop production, while others work to develop advanced ways to produce livestock. Also, bioengineers develop medical technologies to help diagnose diseases in people and to create solutions, such as prosthetic limbs for amputees.

Biotechnology is used in all of the fields involving bioengineering. ***Biotechnology*** is the use of tools and resources to manipulate or model living organisms to meet human needs and wants. Bioengineers work in such diverse fields, there is often confusion about what makes a bioengineer. In this chapter, we will look at three different areas of concentration for bioengineers: biological engineering, agricultural engineering, and biomedical technologies. See **Figure 11-1**. All of these areas of focus use biotechnology.

Professional Aspects

Bioengineers have diverse educational backgrounds. Bioengineers start their careers with bachelor's degrees in biological engineering, agricultural studies, biology, or the medical field. Because of the diverse fields involved with bioengineering, most engineers have a graduate degree in a more specialized area. Associate's degrees can be obtained in biotechnology or one of many biotechnology-related fields, including organic chemistry, biology, cellular biology, or bioscience. People with associate's degrees in these areas often find entry-level jobs as lab assistants or research assistants. These people may also be manufacturing technicians producing biotechnology-related parts, or they may work in quality control for biotechnologies.

Students interested in biotechnology-related fields should take coursework in high school to build their scientific and technical abilities. Suggested high school courses include advanced biology, chemistry, engineering design, algebra,

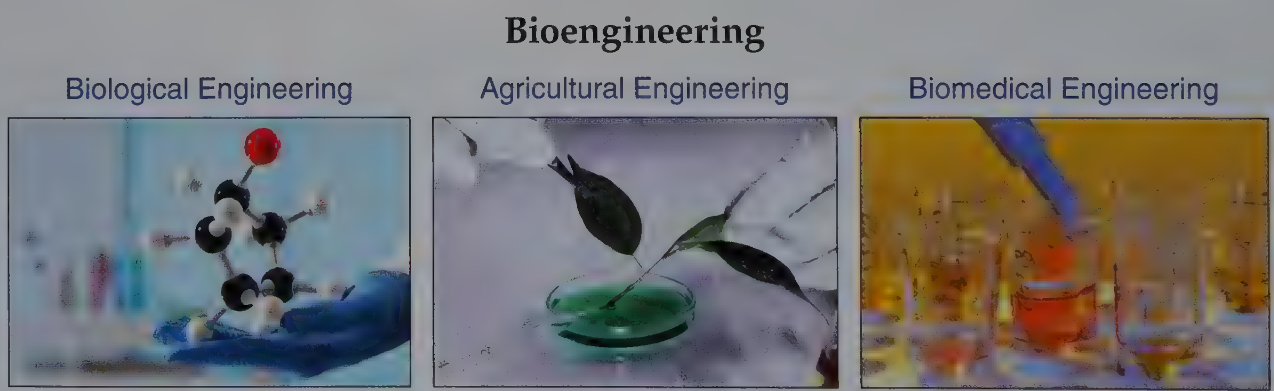

Figure 11-1.

The three major areas of concentration in bioengineering are biological, agricultural, and biomedical engineering.

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and physics. In college, bioengineers take courses in genetic engineering, biochemistry, microbiology, pharmacology, bio-processing, and neuroscience. They may also have degrees in these fields.

Biological, agricultural, and biomedical engineers have many different professional organizations to promote and support their fields. Biological engineers may be members of the Institute of Biological Engineering (IBE) and the Society of Biological Engineering. The IBE is an organization that encourages cooperation between scientists and engineers, develops professional standards for the field of biotechnology, promotes research in biotechnology, and encourages responsible use of biotechnologies. The Society of Biological Engineering actively encourages the integration of biology with technology and promotes bioprocessing, biomedical, and biomolecular applications. Agricultural engineers are represented by the American Society of Agricultural and Biological Engineers (ASABE), which focuses on promoting efficient and environmentally sensitive methods of producing food, fiber, timber, and renewable energy sources. The American Institute for Medical and Biological Engineering (AIMBE) is a professional organization for biomedical engineers.

Principles of Bioengineering

Bioengineers rely on the basic principles of biology as a foundation for their fields of study. Biology can be broken into five fields of study: cell theory, evolution, genetics, homeostasis, and energy.

Cell Biology

Cell biology is the study of cell structures. ***Cells*** are the structural and functional units of all living things. Cells are made up of many different parts. The nucleus of a cell is the largest part and center of the cell. The nucleus holds the DNA information of the cell. A cell reproduces itself by division, **Figure 11-2**. In the simplest form of cell division, a cell splits into multiple cells. The new cells, or daughter cells, contain the same DNA as the original cell. DNA is described later in this chapter.

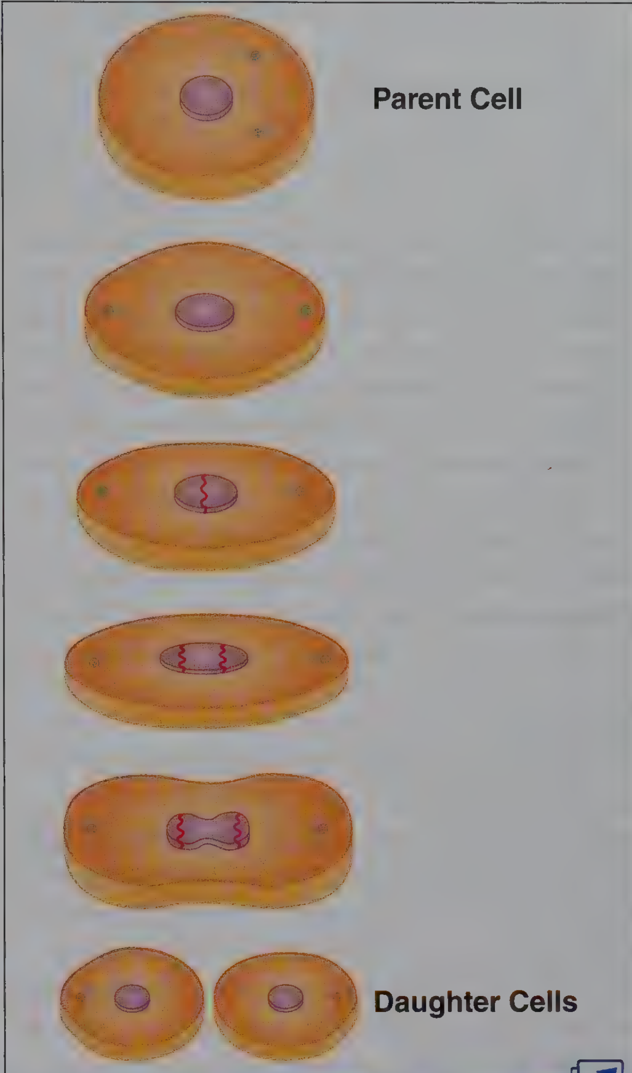

Figure 11-2. Expand learning

When cells divide, the parent cells splits into multiple daughter cells, all containing the same DNA.

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Evolutionary Biology

Evolutionary biology is the study of how organisms and species evolve from different organisms. Some biological engineers study how different animals and plants evolve to adapt to changing environments. One example of evolution is the antifreeze protein in fish in the arctic and Antarctic. The protein allows them to live in cold water without ice crystals forming in their blood. Historically, there have been two methods of change in plants, animals, and people: natural selection and artificial selection.

Natural selection is the ability of living organisms to adapt to their environment through the natural change of characteristics that are needed to help the organism survive. Natural selection allows stronger or better-adapted organisms to survive, while weaker or less-adapted organisms die off. This change occurs slowly over many generations and leads to the changing of an organism's genetic makeup through genetic adaptation. Genetic adaptations include specific bacteria that have become resistant to antibiotics. Over generations, these simple bacteria have developed a survival gene, and a different antibiotic must be used to kill the bacteria.

Artificial selection is the intentional selection of specific traits from animals or plants to make more prominent through breeding. This process allows farmers the ability to help develop animals and crops that fit specific characteristics.

Genetics

Genetics is a field of study focused on the ways in which genes are used inside the cell structure. ***Genes*** are the hereditary unit of living organisms that contain information about the traits from parents and give instruction to the rest of the cell on which traits to pass on to the offspring. Some traits are visible, such as hair or eye color, but others, such as the risks of genetic disorders, are not. Traits are determined by the dominant and recessive genes inherited from the parents. Dominant genes are always inherited over a recessive gene.

A basic knowledge of genes is needed to understand fundamental biological engineering. Genes live in the DNA of living organisms and tell the cell which proteins to build, which leads to the different traits of an individual. Deoxyribonucleic acid (DNA) contains all the genetic instructions for living organisms. DNA can be seen as the blueprint for living objects by telling the cell how to build and expand. DNA is made of two nucleotides made of sugar and phosphates joined by bonds. Nucleotides are the fundamental building block of DNA and RNA. Nucleotides are made of a base, sugar, and phosphate. Attached to the sugars in the bond are bases. There are four possible bases: guanine (G), cytosine (C), adenine (A), and thymine (T). Guanine bonds with cytosine, and adenine bonds with thymine. The combination of these bases makes each person's DNA unique. The structure of the DNA is called a double helix because of its twisting structure. This double helix provides the necessary information for the proteins to determine the structure of an organism. Every living object has a unique DNA code. See **Figure 11-3**.

Ribonucleic acid (RNA) is similar to DNA, but it has a few distinct differences. First, RNA is typically a single strand and does not have the double helix structure found in DNA. Second, RNA substitutes uracil (U) for thymine (T), so the RNA bases are guanine (G), cytosine (C), adenine (A), and uracil (U). RNA transmits the genetic information from DNA in the nucleus to the part of the cell called the ribosome in order to create proteins.

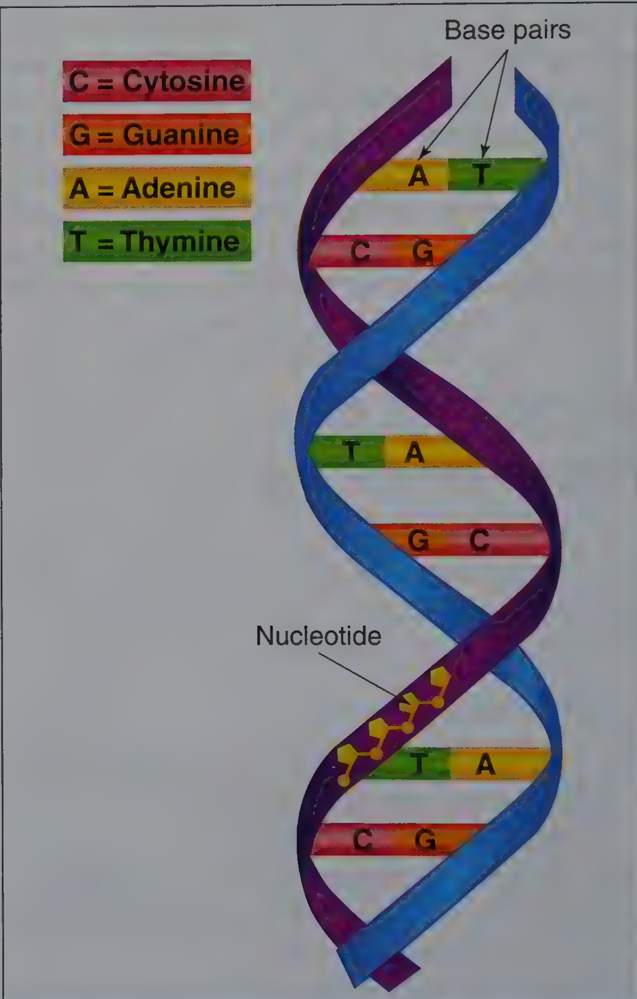

Figure 11-3.

The double helix is connected by bonds of guanine, cytosine, adenine, and thymine.

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Homeostasis

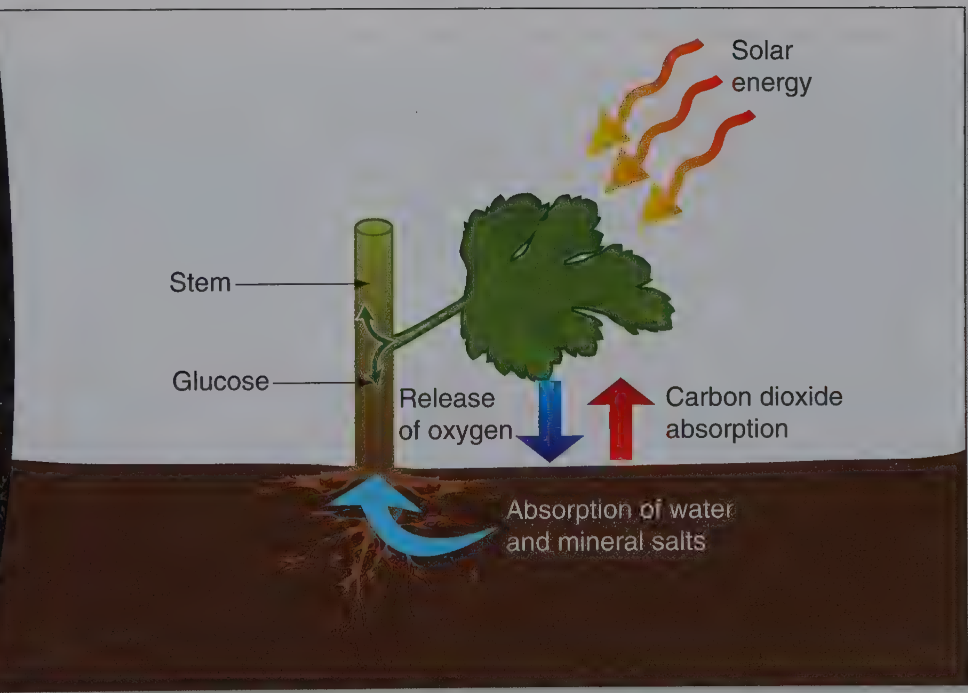
Have you ever been rushing to class and started sweating? You used homeostasis to help cool your body. ***Homeostasis*** is the ability of an organism to regulate itself in order to maintain a constant state. Homeostasis is critical for all organisms because it allows for regulation of body temperature. Being able to regulate our own temperature is an example of how homeostasis allows us to adapt to different environments. Along with temperature, the body uses homeostasis to control the blood sugar levels in the body. The human pancreas releases insulin and glucagon when the body needs to lower (using insulin) or raise (using glucagon) blood sugar levels.

Homeostasis is a major part of many disciplines in bioengineering because it allows engineers to explore the different environments in which organisms live. Also, engineers have developed solutions to assist some living organisms to adapt to different environments. For example, engineers have developed cooling systems for race car drivers that fit into their protective gear to help the drivers body stay at a constant temperature and not become too hot while driving a race. We also see homeostasis in many different systems outside of biotechnology, including the way mass transit systems use self-regulation computer and sensor systems to ensure passenger safety.

Energy

The final area of biology used by bioengineers is energy. The study of biological energy is focused on how organisms survive through processing sources of energy, such as food. In most organisms, energy is stored in cells as carbohydrates, lipids, and proteins. This stored energy is used to help move, grow, and develop an organism. We use the foods we eat for energy and to help us grow and develop. This is similar to how plants use the process of photosynthesis, which is the absorption of water and sunlight to produce food, **Figure 11-4**. Photosynthesis uses water, sunlight, and carbon dioxide to create a sustainable system for plants. Plants absorb water through their roots. They absorb sunlight through a part of their cells called *chloroplasts*. They can also absorb carbon dioxide through tiny pores in their leaves called *stomata*. The combination of water, sunlight, and oxygen is turned into glucose to feed the plant, and oxygen is released into the atmosphere for other living organisms to use.

Figure 11-4.
Photosynthesis is a type of energy process in which the roots of a plant absorb water and mineral salts, while the leaves absorb solar energy and carbon dioxide as they release oxygen.



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History of Biological Engineering

Biological and agricultural engineers rely heavily on biotechnology to solve problems and find new discoveries. Engineers also create new biotechnologies. One of the most critical biotechnological methods used today is the extraction, manipulation, and analysis of DNA.

The ways we use DNA today can be traced back to 1665, when Robert Hooke first discovered and named a *cell* while looking down a microscope. It was in 1839 that two German biologists, Matthias Schleiden and Theodore Schwan, wrote that all living organisms are made of cells. In 1856, Gregor Mendel discovered that each organism contains genes (although they were not called genes at the time) from their mother and father. Biologists began looking into DNA during the early 1900s. In 1953, James Watson and Francis Crick developed their detailed view of DNA. Watson and Crick developed the model without the ability to actually see DNA because of the size of the cell parts they were investigating.

It was the discoveries of these early biologists that led humans to the advanced technologies of DNA manipulation, genetic engineering, and DNA fingerprinting. Without the foundational principles of biology and creative thinking of early scientists, we would not have access to the common biotechnologies we use today.

Bioengineering Applications

Engineers in biological fields use the five basic areas of biology discussed in this chapter as a foundation for the problems they solve. Along with the five primary areas of biology, engineers also must rely on many other fields of engineering, such as mechanical engineering, materials engineering, chemical engineering, and computer engineering, to help solve problems. Because many areas of engineering are used in solving real-world biological problems, the applications of biological engineers reach into different fields. The three primary fields are biological engineering, agricultural engineering, and biomedical engineering. All three of these biological engineering fields rely heavily on biotechnology as a tool. Biotechnology is also seen as a way to develop solutions to problems faced by bioengineers.

Biological Engineering

Biological engineers use many different biological principles and tools to solve biological problems. Some biological engineers work specifically with biological problems focused on many different fields. Biological engineering has a dramatic impact on our society and environment because of the focus on living materials and waste.

Genetic Engineering

Genetic engineering is done in agricultural settings to change the properties of plants. Biological engineers work with the genomes of living objects to change the taste, growth properties, plant durability, and other characteristics. The genome is the entire genetic heredity of an organism. The genome contains the exact information needed to reproduce an exact replica of an organism.

Engineers use transgenesis and cisgenesis to change plant properties. Engineers use transgenic engineering by introducing a complete new characteristic or trait into an animal or plant. In transgenic engineering, the trait is from a completely different species. The process of cisgenesis involves engineering introducing a trait into an animal or plant that could naturally occur because the trait is found in a similar plant or animal.

Biomass

Biomass is biological materials that are used as a source of energy to produce heat or electricity. People use biomass in many ways. Biological objects that are commonly used include wood, food waste, yard waste, hydrogen gas, and alcohol fuels.

Biological engineers are currently working on ways to improve the generation of biological materials to use as biomass. Methods to improve biomass production include genetically engineering plant life, such as trees, to grow more

Science

Organization of Living Things

Bioengineers may deal with all types of living things. How are living things divided and identified? A biological taxonomy, or way of classifying things, helps group living things together by certain traits. There are many different levels of organizing living things. The most general way to group living things is by kingdom. Other more specific groupings include phylum, class, order, family, genus, and species.

Common kingdom divisions include fungi, plants, and animals. There are also kingdoms that contain less complex organisms, such as bacteria. Every living thing can be categorized into these kingdoms.

The genus and species groupings are more specific. In fact, each type of organism is labeled using its genus and species. A family dog is classified as *Canis familiaris*. The terms given for an organism's genus and species are in the Latin language. The genus is always capitalized, and the species is always given in lowercase letters. In this example, the term *Canis* is the genus, which is Latin for *dog*. The species, *familiaris*, is Latin for *domestic*. The term *Homo sapiens* refers to all modern human beings. Prehistoric humans were classified by other species, though the genus remains the same.

quickly and in more diverse climates to improve the amount of biomass for humans to burn for energy. See **Figure 11-5**.

The use of biomass as an energy source has a mixed environmental impact. The burning of biomass produces carbon dioxide, just like the use of fossil fuels. However, using biomass for fuel reduces agricultural waste and can help eliminate waste products that may go to a landfill. Another positive aspect is that biomass materials can be grown again quickly and can be produced domestically.

Figure 11-5.

Biomass goes through a conversion process before being changed for use to provide heat or electricity. The bits of wood shown here can be burned for heat.

nostal6ie/Shutterstock.com

To use biomass effectively, bioconversion is necessary. There are two types of bioconversion: biochemical and thermochemical.

Biochemical Conversion

Biochemical conversion is a method of bioconversion that uses enzymes and other microorganisms to convert biomass materials into energy sources. Microorganisms are extremely small organisms, often bacteria or fungi, that live almost everywhere on earth, including inside living organisms. Microorganisms are very important because they have specific traits that help other organisms live. There are three methods of biochemical conversion: fermentation, anaerobic digestion, and composting.

Fermentation is a chemical process that uses microorganisms to decompose a biomass material to create the liquid fuel alcohol. The process of fermentation includes using glucose, fructose, and sucrose into energy by using yeast. When the yeast reacts with the glucose, fructose, and sucrose, it produces carbon dioxide and alcohol. Fermentation is most commonly used by biological engineers to create ethyl alcohol, or ethanol. See **Figure 11-6**. Ethanol is a fermented chemical used for fuel. Ethanol is blended into gasoline to help reduce the amount of oil used in each gallon of fuel. If you visit a gas station, you will notice a sticker that says, "Contains up to 10 percent ethanol." This means the fuel is a mixture of 90% oil-based fuel and 10% ethanol, or plant-based fuel. The fermentation process is also used to produce methanol, which is used in many race cars.

Anaerobic digestion is a process that uses microorganisms to degrade biological material in an environment without oxygen. This process is typically conducted using tanks that limit the amount of oxygen into the system. Once the microorganisms break down the biodegradable material, the gas methane is produced. See **Figure 11-7**. Methane can be used as heating fuel or as a method to power electrical generators. Methane use is growing in the agricultural facilities because it allows farmers to use the animal and plant waste on their farms as a method to fuel their agricultural operations. Have you ever seen exhaust pipes on a landfill? These exhaust vents are allowing methane gas to escape the landfill, and you can often see a flame burning on the vent. While anaerobic digestion creates the methane gas as discussed, it also leaves behind a solid material that can be used as a fertilizer.

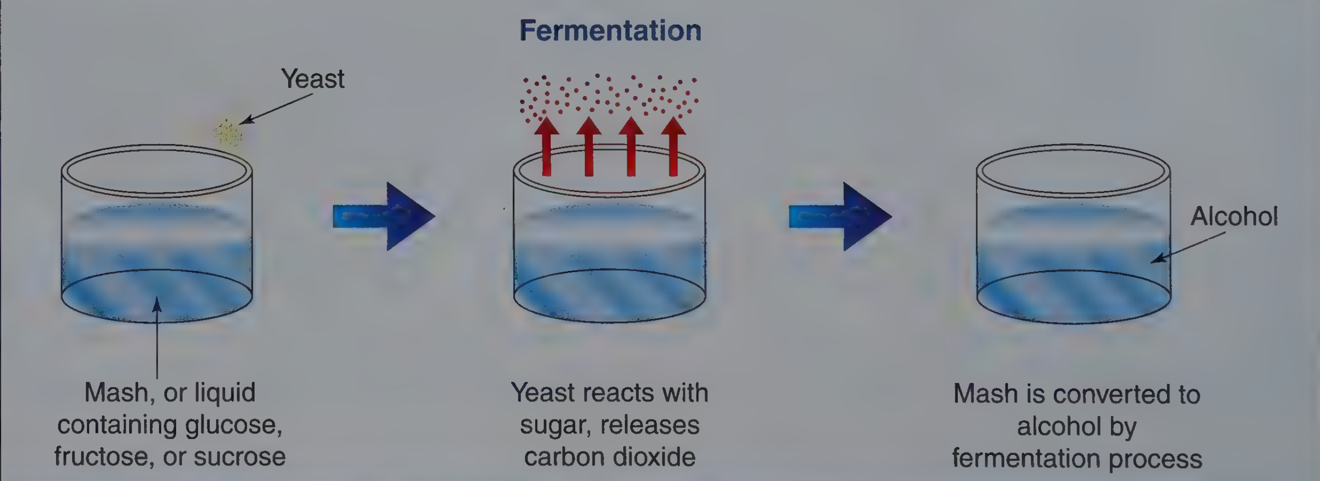

Figure 11-6.

Corn is converted by fermentation before it can be used for fuel.

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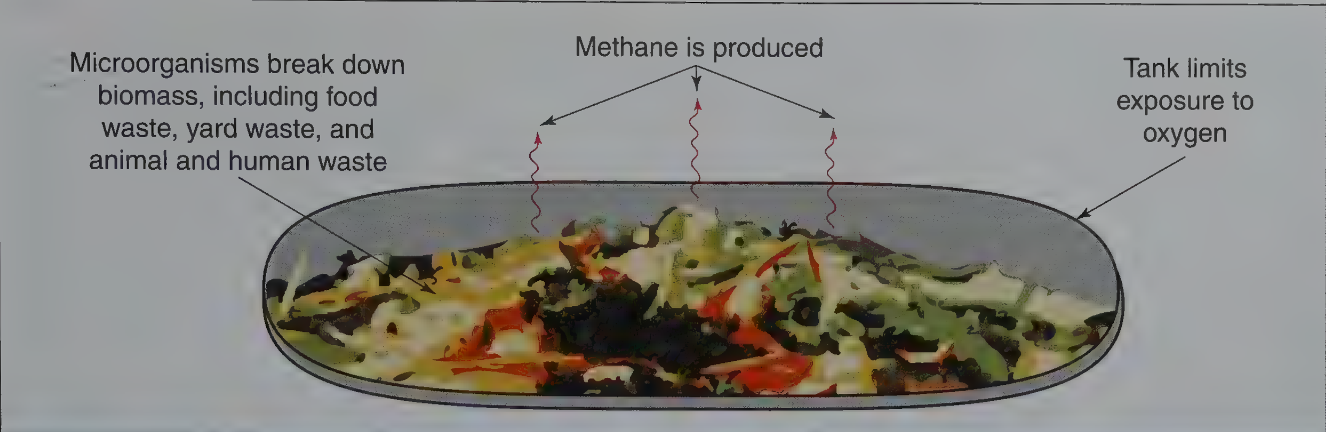

Figure 11-7.

The anaerobic digestion process removes oxygen from a tank full of biomass and exposes the biomass to microorganisms to create methane.

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Composting is a method of creating piles of biomass and allowing the natural organisms to break down the biological composition of the material. See **Figure 11-8**. Composting has by-products of heat, carbon dioxide, and ammonia.

The final output is ***compost***, which is a solid material used to fertilize agricultural crops and other plant life. The compost is rich in nutrients and is commonly used in organic farming environments. People can create small compost piles in their own outdoor spaces, using their food and lawn care waste to create nutrient-rich compost. See **Figure 11-9**.

Figure 11-8.
Composting is a bioconversion process that takes various forms of waste and uses air and heat to convert the waste into nutrient-rich compost.

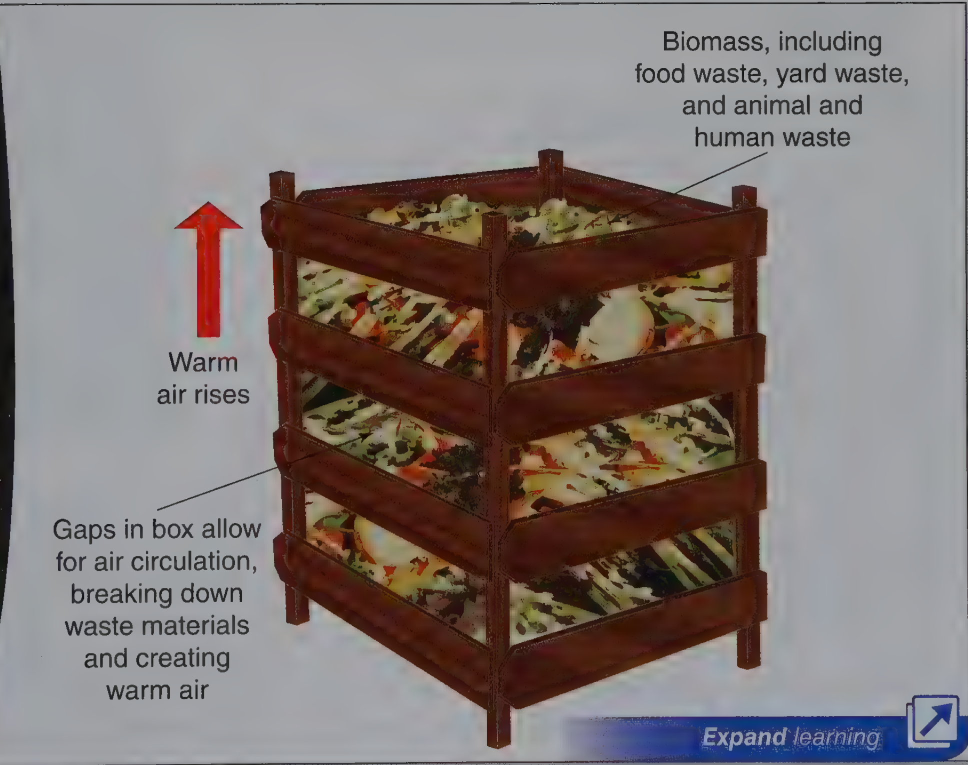

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Figure 11-9.
Everyday waste items, such as food and lawn care waste, can be used to make compost for the home.

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Going Green

Vertical Farms

The world population continues to grow. In 1800, the world had a population of 978 million people. In 1900, the world population was 1.6 billion people. The current population is about 7 billion people. It is anticipated that by the year 2050, the world population will have increased to over 9 billion people. As a society, we must be able to produce enough food to feed the world population. Through more efficient farming and improved biotechnologies, we have been able to adapt to the growing population, and we will need to continue to adapt in the future.

One idea, proposed by Dr. Dickson Despommier, a professor at Columbia University in New York City, is to create vertical farms. Vertical farms are designed to grow *up* instead of *out*. They could be used in urban areas with very little land and would be built high in the air like a skyscraper. The vertical farm would need to have irrigation, lighting, and a method of processing the fruits and vegetables. Also, the vertical farm would need to be environmentally friendly, safe, cheap to build and maintain, and easily adaptable to different types of produce. See **Figure A**.

Figure A.

Chris Jacobs

Thermochemical Conversion

Thermochemical conversion uses heat to create a chemical change in biological material. Thermochemical conversion is currently the most common process of bioconversion on earth.

The most direct form of thermochemical conversion is *combustion*, which is the burning of wood, municipal waste, or other biomass to create heat or to provide steam to power electrical generators. Combustion is the chemical reaction between an oxidant and fuel that releases energy in the form of heat and light. Oxygen and biomass material are needed to create combustion for thermochemical conversion. Thermochemcial conversion is also used in many industrial applications to heat different materials for manufacturing processes. The use of a fireplace or woodstove in a home is a good example of thermochemical conversion. The wood, which was a living plant, is burned to provide direct heat to the household.

Pyrolysis is another thermochemical process used with biomass. *Pyrolysis* involves breaking down biological materials with heat and reduced oxygen. Pyrolysis is the decomposition of organic materials without oxygen or water used and places the material to be decomposed under high levels of heat and pressure. Instead of burning the material, it chars material. Have you ever used charcoal? Charcoal is created through pyrolysis by heating wood and limiting the amount of oxygen available during the process. Instead of the wood burning, it is charred and the energy is available to be used in cooking with a charcoal grill. See **Figure 11-10**.

Figure 11-10.

The thermochemical conversion process of pyrolysis is used to create charcoal, which can then be used for cooking and heating.

Matt Antonio/Shutterstock.com

The third method of thermochemical conversion is the process of gasification. *Gasification* is the process of turning biomass into carbon dioxide and hydrogen through a controlled amount of high temperatures and oxygen. This process produces syngas, or synthetic gas, which is used as a fuel. The process is different from other methods because of the extremely high temperatures and the carefully controlled amount of oxygen used. Almost any type of organic material can be used in the gasification process. Gasification, while different from the other processes, actually relies on the other methods of thermochemical conversion at different stages of the process. The organic material is placed under high levels of heat and pressure to eliminate moisture to create a "char" product. The char is then combusted (burned) when mixed with oxygen, and it produces carbon dioxide. Once the char interacts with the carbon, carbon monoxide and hydrogen are produced.

Agricultural Engineering

Agricultural engineering is a branch of biological engineering focused on crop and livestock production. Many of the same bioconversion principles also relate to agricultural engineering. Agricultural engineering also relies on principles from other fields of engineering discussed in this text, such as electrical engineering, mechanical engineering, and chemical engineering. Agricultural engineers develop solutions to improve crop production, animal production, and the processing of food products.

Crop Production

Historically, engineers have been able to change the characteristics of a plant or animal through the use of selective breeding. As previously discussed in this chapter, artificial breeding is when crops or animals with desired traits are bred together to create more prominent desired features.

This process, often called selective breeding, allows engineers to select the specific traits they want to improve without actually genetically modifying plants and animals.

The current use of genetic engineering by agricultural engineers, however, is changing species through the use of biotechnology to alter their DNA. The most common product of agricultural engineering is genetically engineered crops. ***Genetically engineered crops*** are plants whose genetic structure has been changed intentionally. Genetically engineered plants are created for many reasons, but the intent is always to improve the quality, efficiency, and production ease of a crop.

Agricultural engineers currently focus on four primary methods of improving the quality, efficiency, and production ease of a specific crop. First, engineers have developed plants that are resistant to herbicides. The crops are engineered using genes from other plants to allow the crop to degrade the active ingredients in herbicides to make them harmless to the crop. ***Herbicides*** are chemicals sprayed by farmers to eliminate weeds that may damage a specific crop. See **Figure 11-11**. By producing plants that are resistant to herbicides, farmers can spray herbicides on their fields without the fear of damaging their own crops.

Second, farmers create plants that can resist insect pests and diseases. Pests and diseases can reduce the amount of good product a farmer receives from his field. Agricultural engineers are always concerned about the farmer's production per acre, also known as the ***crop yield***. By using the genetic traits of different plants with a natural resistance to specific diseases or pests, and combining these resistant traits with the genetic makeup of corn, soybeans, or other crops, engineers have been able to produce seeds with resistant traits. Also, agricultural engineers have developed vaccines for plants that help plants fight specific fungi that may damage the crop.

Third, agricultural engineers look to develop plants that can survive extreme environmental conditions such as drought or frost. These plants can provide a farmer a more consistent yield, without major fear for environmental conditions which may heavily damage a crop. Engineering crops for different environmental conditions also allows plants to be grown in environments that are not natural for the plant. For example, this type of technology allows a person to grow a dry-weather plant in a humid environment. Engineers have also developed a genetically engineered bacteria that can be used with plants to help them resist frost damage.

Figure 11-11.
This farmer is spraying his crops with herbicides, which can kill weeds without harming the crop.

Frederico Rostagno/Shutterstock.com

Tools

Gene Gun

Biotechnology has a few tools specific to the field, but one of the most important and influential tools is the gene gun. The gene gun is a tool used by bioengineers to inject cells with genetic information.

Millions of particles can be coated with DNA. These are injected into various types of cells using the gene gun. The gene gun is typically injected into a petri dish full of cells, and not all of the cells survive the process.

The tool was designed by scientists at Cornell University in the 1980s and is commonly used today. The gene gun was originally designed to inject genetic information into plant cells. Today, however, it can be used on other types of cells, including animal cells.

Figure 11-12.

Tomatoes have been used in the efforts to genetically engineer produce to last longer and have better flavor.

Fotokostic/Shutterstock.com

And fourth, engineers are constantly developing produce with new characteristics to improve nutritional value, have a longer shelf life, or to have a different flavor or texture. The first large-scale example of using genetic engineering to modify a plant is the creation of the Flavr Savr tomato. The Flavr Savr tomato, created in the early 1990s, was genetically engineered to resist rotting. This resistance meant the tomato would have a longer shelf life and taste better when it reached the consumer, **Figure 11-12**. Production on the Flavr Savr tomato ceased in the late 1990s because of the cost to create the tomato plants.

Genetically engineered plants involves adding one or more genes to a plant. This process is usually completed in a laboratory by introducing the new gene into the genetic makeup of the plant. All plants and seeds developed by the plant in the future will have the altered genetic makeup. The process is completed using a gene gun, which injects the new gene into the existing genetic makeup.

Animal Production

Agricultural engineers use biotechnology in many ways to improve the production of livestock. Much like the use of engineering with crop production, the goal for agricultural engineers with livestock is to improve the efficiency of the livestock operation to provide a more profitable operation for the farmer, while also paying attention to the environment and the quality of life for animals. More specifically, engineers want to be able to get more milk, meat, eggs, or other products from animals.

The way agricultural engineers improve livestock efficiency is through the use of biotechnology. Medicines and reproductive technologies are engineered for livestock. Also, recently, engineers have used cloning to begin production of various animals, although the cloned livestock are not currently used for human consumption. Cloned livestock are typically used for breeding purposes. The US Food and Drug Administration (FDA) has stated that livestock that are direct clones should not be in the food supply, but offspring from clones are safe for consumption.

Engineered animal medicines are common in agricultural settings. Vaccines and medicines have been used on livestock for many years. One recent example is the bovine somatotropin (BST), which is also called the bovine growth hormone (BGH). There is a natural chemical produced in cattle, BST, to encourage growth and help produce milk. See **Figure 11-13**. Genetic engineers have created a synthetic version of BGH to inject in cows to greatly enhance the amount of milk produced. Some farms do not inject their cattle with BGH, and as a result, organic dairy products and other products without BGH are available. See **Figure 11-14**.

Historically, engineers have used biotechnology to assist in the reproduction of animals. Using selective breeding and related technologies developed to assist the process, engineers were able to create more desirable characteristics in livestock.

Engineers create genetically modified animals by manipulating the DNA of the animal to alter characteristics. Some animals have been modified for many years. For example, engineers have created many different types of mice to be used for testing of different medicines or other products.

Figure 11-14.

Concern over milk produced from cows injected with BGH has led to the production of milk that is free from BGH.

Goodheart-Willcox Publisher

In 1996, genetic engineers in Scotland created a genetically engineered sheep named Dolly, which was an exact clone of another sheep. ***Cloning*** is the use of genetic engineering to create an exact copy of a living organism. While mice and sheep have been cloned, no animals have been cloned to be put into the food market for human consumption. The genetically engineered animal most likely to enter the food market is the Atlantic salmon. Genetically engineered salmon are currently under review by the FDA.

Figure 11-13.

Cows that have been injected with BGH produce more milk than cows that are not injected.

IdeaStepConceptStock/Shutterstock.com

Agricultural engineers are currently working to create genetically engineered fish that may be safe for human consumption. These salmon are designed to grow much quicker in a controlled environment. See **Figure 11-15**.

Processing of Food Products

Food processing is the taking of raw products or ingredients and preparing them for human consumption. Food processing can incorporate different steps depending on the product. Food processing involves sorting, cleaning, preparing, packaging, and shipping food products. Engineers and technicians are needed for each step of food processing.

Engineering is used in sorting and cleaning food products in many different ways. Engineers design ways to keep the food products at safe temperatures and use appropriate solutions and methods to clean the food products. Also, engineering solutions are created to more efficiently sort food precuts. Conveyor systems and mechanical devices sort specific products by weight or size.

Engineering solutions are also created to solve challenges associated with preparing, packaging, and shipping foods. Many foods are processed by combining different products, such as produce and meat, to create ready-to-cook meals for consumers. These types of products follow safe food guidelines. Engineering is used to help create the products. For example, manufacturing techniques are used to combine and mix food materials.

Once foods are processed to the desired format, they must be packaged and shipped. Biological and agricultural engineers are part of the packaging and distribution steps. Food must be safely packaged and distributed to consumers, taking into account temperatures and the amount of time products can be consumed. Some foods use preservatives to make them last longer, and other produce is shipped and delivered quickly to ensure a fresh taste.

Biomedical Engineering

We only need to look at ourselves to see the greatest impacts of biological engineers. Biomedical engineers take the foundations of biology including cell theory, evolution, genetics, homeostasis, and energy, along with technologies to create medicines, biotechnologies, and support systems to help us reach our human potential.

Figure 11-15.
Genetically engineered salmon are being bred to grow more quickly throughout the year.

Konstantin Karchevskiy/Shutterstock.com

As previously discussed, biological engineering typically deals with bioconversion. This differs from biomedical engineering, which is typically defined as the use of support systems to help identify diseases and physical mechanisms to help people. While they can be seen as different areas, they work together in many ways.

Biological Engineering with Human Beings

Great strides have been made in medical treatments over the past 200 years. What was once considered a life-threatening disease may now be treated with a simple antibiotic or other medical procedure. Biological engineering advancements have allowed people to live longer and healthier lives especially through the use of medicines, transplants, and cell treatments.

A transplant is the transferring of an organ from one living being into another living being. Early transplants began with doctors transplanting skin in the 1800s, but the first organ transplant was the kidney in 1951. Liver and lung transplants followed in the 1950s. One of the most famous transplants was of a heart in 1967. Currently, over 100,000 kidney transplants and 3,000 heart transplants occur in the world each year.

Cell therapy is used to introduce new cells into the body to treat disease. Some of the methods of cell therapy include cell replacement therapy, gene therapy, and stem-cell therapy. Replacement therapy replaces old, damaged cells with healthy cells to cure diseases. Gene therapy is most commonly performed by using DNA to encode a properly functioning gene to replace a damaged gene. Another method of cell therapy makes the use of stem cells. Stem cells are nonspecific cells that can be programmed by engineers to treat many different issues in the human body. Adult stem cells are most commonly found in bone marrow.

No technology has had greater impact on people than the use of medicines. Biological engineers work to develop solutions to everyday diseases. Since 1970, genetic engineering has been used to create drugs, but even prior to the increase in genetic engineering, biological engineers were creating medicines, such as penicillin. Penicillin, created in 1928, uses natural microbes (mold) placed into the human body to counteract a bacteria. Still to this day, over 100 prescription drugs are created using microbes. Over 100 drugs are also produced using extracts from plants. One example of a plant-based medicine is Madagascar periwinkle, whose extracts have been used to treat leukemia and Hodgkin's lymphoma. See **Figure 11-16**.

Figure 11-16.

Biomedical engineers research and use microorganisms to create medicines we use every day.

docent/Shutterstock.com

Genetic engineering has expanded the ability to treat people beyond medicines based on microorganisms or extracted plant chemicals. Genetically engineered pharmaceuticals can be created using human DNA as a basis to ensure patients do not have bad reactions. Also, engineers can take different traits from genes and manipulate them into a drug for multiple uses. Genetically engineered vaccines are also used on people because these vaccines do not contain actual living organisms, which helps reduce the risk of allergic reactions.

Biological engineers also use monoclonal antibodies to target specific diseases. ***Monoclonal antibodies*** work like natural antibodies in the body by finding the unwanted germ and attacking. Using monoclonal antibodies, engineers are able to attach certain treatments to the antibodies and provide medicine or trace the unwanted germs. See **Figure 11-17**. This process targets the direct problem and helps doctors eliminate the disease. Future solutions to problems by biological engineers will rely heavily on monoclonal antibodies. Engineers and doctors have just scratched the surface of this biotechnology that has only been available for 30 years.

Design

Genetic Screenings

Bioengineers have the goal of solving problems related to human life. Engineers have designed ways to perform genetic screenings to provide information about the genetic makeup of individuals and potential diseases they may encounter.

Genetic screenings are conducted on individuals for many different reasons. Screenings can be conducted on adults to determine potential diseases they may encounter or possibly pass on to their children. Genetic screenings are also conducted on newborn babies to determine any potential risks for genetic diseases.

Over 2,000 genetic screenings have been designed. Some common screenings that may show potential links to diseases include thyroid disorders, cystic fibrosis, breast cancer, and congenital heart defects.

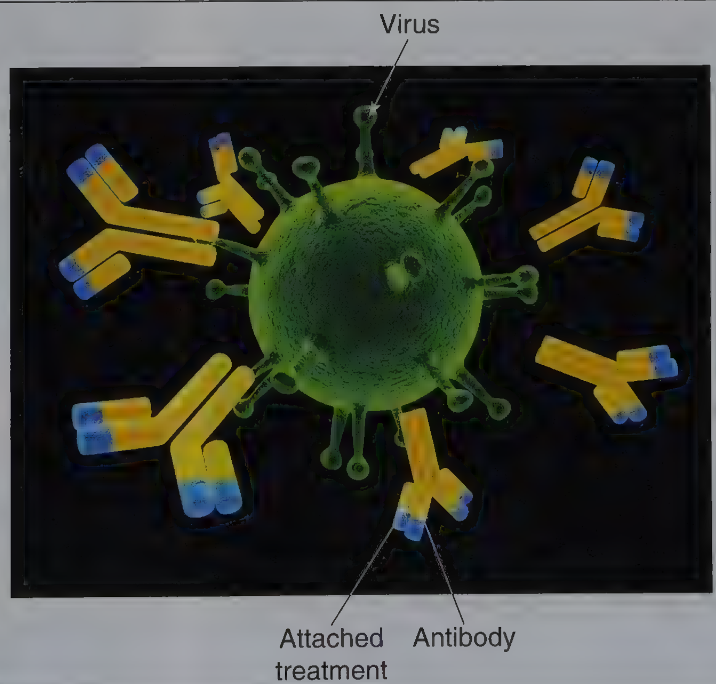

Figure 11-17. Monoclonal antibodies use treatments attached to antibodies to better fight viruses.

Sebastian Kaulitzki/Shutterstock.com

Medical Technologies

Medical technologies is another field of engineering related to biological engineering and biotechnology. Medical technology is the use of technology to diagnose, treat, or monitor medical conditions in humans. Medical technology is a large field and requires skills from many different engineering disciplines such as electrical engineering, mechanical engineering, and materials engineering.

Engineers create medical technologies to diagnose diseases or conditions. Have you ever been to a doctor and had an x-ray? An x-ray machine is a medical device that is used to observe and give an image of the dense areas of the body, such as bone. Over time, devices have become more detailed through engineering advancements such as the computerized tomography (CT) scan, which produces a 3-D image inside an object. For other uses, engineers have created tools like the magnetic resonance imaging (MRI) scanner to view detailed images of the inner components of a human body. The development of these biotechnologies relies heavily on engineering concepts associated with electronics, mechanics, material properties, and biological engineering. See **Figure 11-18**.

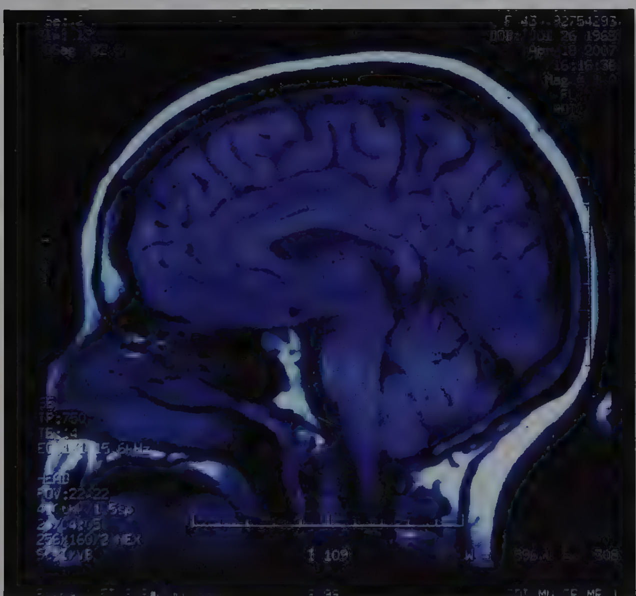

Figure 11-18.

This MRI of a human brain was possible because of the developments of biotechnologies by biomedical engineers.

Mark Herreid/Shutterstock.com

Medical technologies are also produced to help treat medical conditions. Unlike biological solutions, such as medicines, engineers develop mechanical solutions needed to assist people. Prosthetic limbs are engineered to meet the needs of individuals missing a specific limb or part of their body. Prosthetic devices are becoming more advanced. Engineers have developed prosthetic devices that have greater control and mobility. See **Figure 11-19**.

Throughout history, prosthetic devices have changed dramatically. While prosthetics were once made of wood or metal, engineers currently use advanced forms of plastics to create prosthetic devices. These plastics provide excellent strength while remaining lightweight.

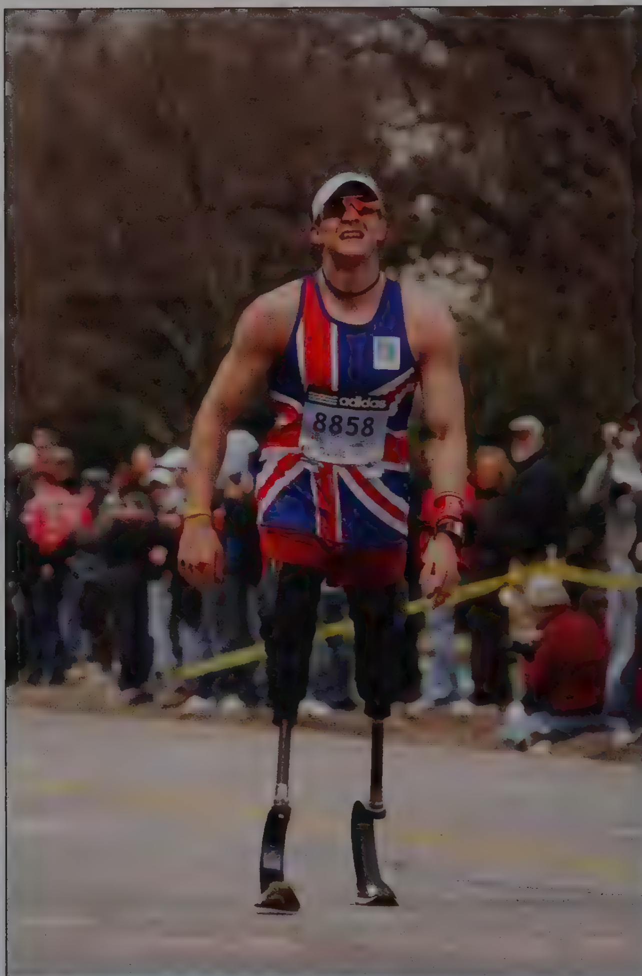

Figure 11-19.

Advanced prosthetic devices have been developed and improved by biomedical engineers.

John Kropewnicki/Shutterstock.com

Engineers also use myoelectric technology to develop prosthetic devices that can be controlled by a patient's nervous system and muscles. This allows patients to use prosthetic devices that move and respond to human controls.

Tissue engineering is a field of bioengineering focused on restoring, maintaining, or enhancing tissue or organs in the human body. Tissue engineering is also referred to as regenerative medicine. Research is currently being conducted, and bioengineers are creating tissue and organs in labs to replace and improve human function. Using technological tools, the biological engineers have created new valves for hearts, found new ways to improve prosthetic devices, and built human tissue to test cures for diseases. Engineers grow and test tissue and organs in a laboratory.

Ethics

Bioengineering deals with many sensitive issues, such as life, human growth, the environment, and economics. When working in the field of biotechnology, engineers must have a grounding in their own morals and the biotechnological field's ethical and moral foundation.

Ethical questions must be considered when we look at how we change living beings and nature. Bioengineers must consider the influence their designs will have on all individuals and living creatures. When engineers clone different animals, they have a responsibility to use ethical practices. When engineers design new chemicals to treat crops, they must consider how their chemicals will influence the environment as well as the consumers who buy their products.

Biological Engineering in Action

Biological engineers have developed many different technological advances for many different industries. One of their most valuable discoveries is the technology to perform DNA fingerprinting. ***DNA fingerprinting*** is a method used by forensic scientists to identify humans by their genetic makeup. DNA fingerprinting is most commonly used in criminal investigations and to determine heredity information. See **Figure 11-20**.

Because of advancements in biology theory and the technical experience of biological engineers, we are now able to "fingerprint" individuals with almost 100% accuracy. The basic process requires breaking apart the DNA samples with a restriction enzyme, placing the DNA pieces in a special gel, adding an electronic charge to

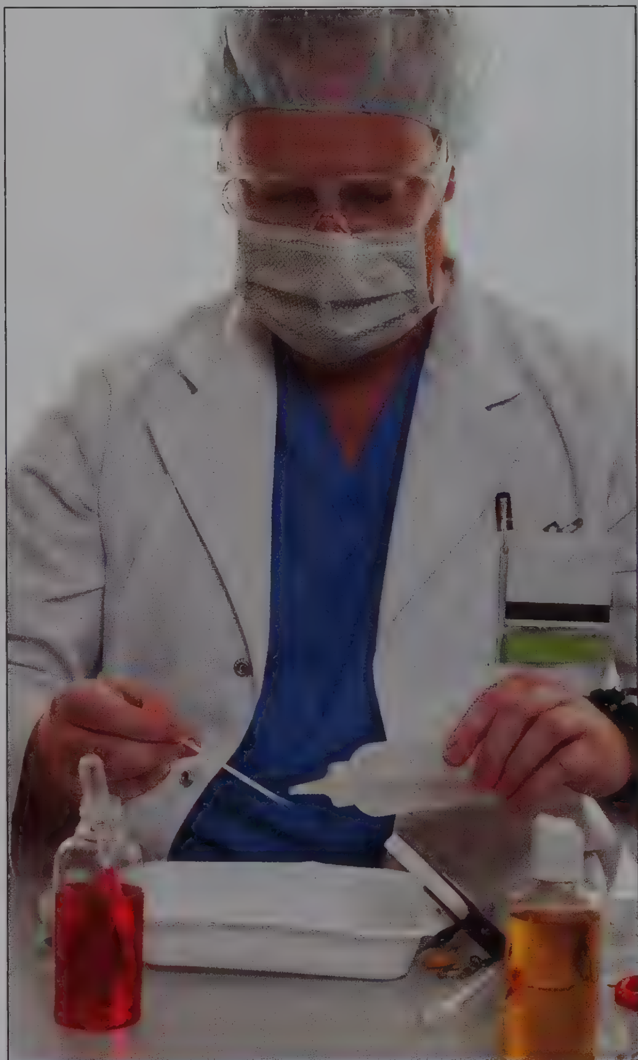

Figure 11-20.

Forensic scientists investigating crime materials in laboratory use DNA fingerprinting to get information.

Leah-Anne Thompson/Shutterstock.com

arrange the pieces, and measure the length of the pieces. See **Figure 11-21**.

DNA fingerprinting can be done with almost any part of the human body or any piece of material from a human. Blood, saliva, skin, and hair are commonly used. Because DNA is a stable material, the DNA material will not change over time and can stay intact for many years. The Federal Bureau of Investigation (FBI) has created a database of DNA samples from crime scenes.

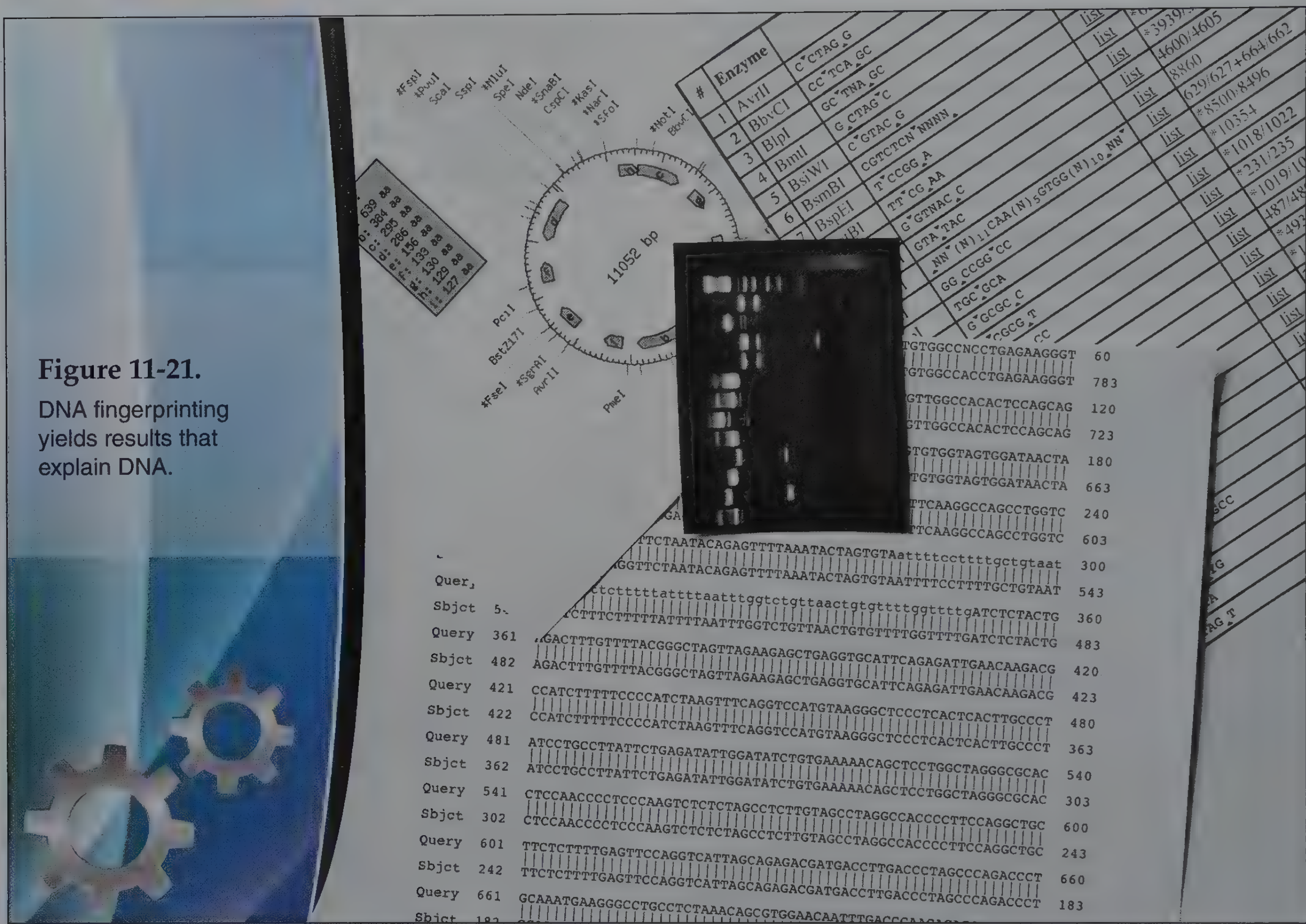

Figure 11-21. DNA fingerprinting yields results that explain DNA.

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Summary

- Bioengineers create energy-production methods from biological matter, safer food supplies to consume, and technologies to investigate illnesses. All of these areas of focus use biotechnology.
- Because of the diverse fields involved with bioengineering, most engineers have a bachelor's degree and a graduate degree in a more specialized area.
- The biology used by bioengineers can be broken into five fields of study: cell theory, evolution, genetics, homeostasis, and energy.
- Cells are the structure and functional units of all living things.
- Two methods used in evolutionary biology are natural selection and artificial selection.
- Deoxyribonucleic acid (DNA) contains all the genetic instructions for living organisms.
- Homeostasis is a major part of many disciplines within bioengineering because it allows engineers to explore the different environments in which organisms live.
- The study of biological energy is focused on how organisms survive through processing sources of energy.
- The two types of bioconversion are biochemical conversion and thermochemical conversion.
- Agricultural engineers develop solutions to improve crop production, animal production, and the processing of food products.
- Biomedical engineering deals with human-related organisms and the use of support systems to help identify diseases and physical mechanisms to help people.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

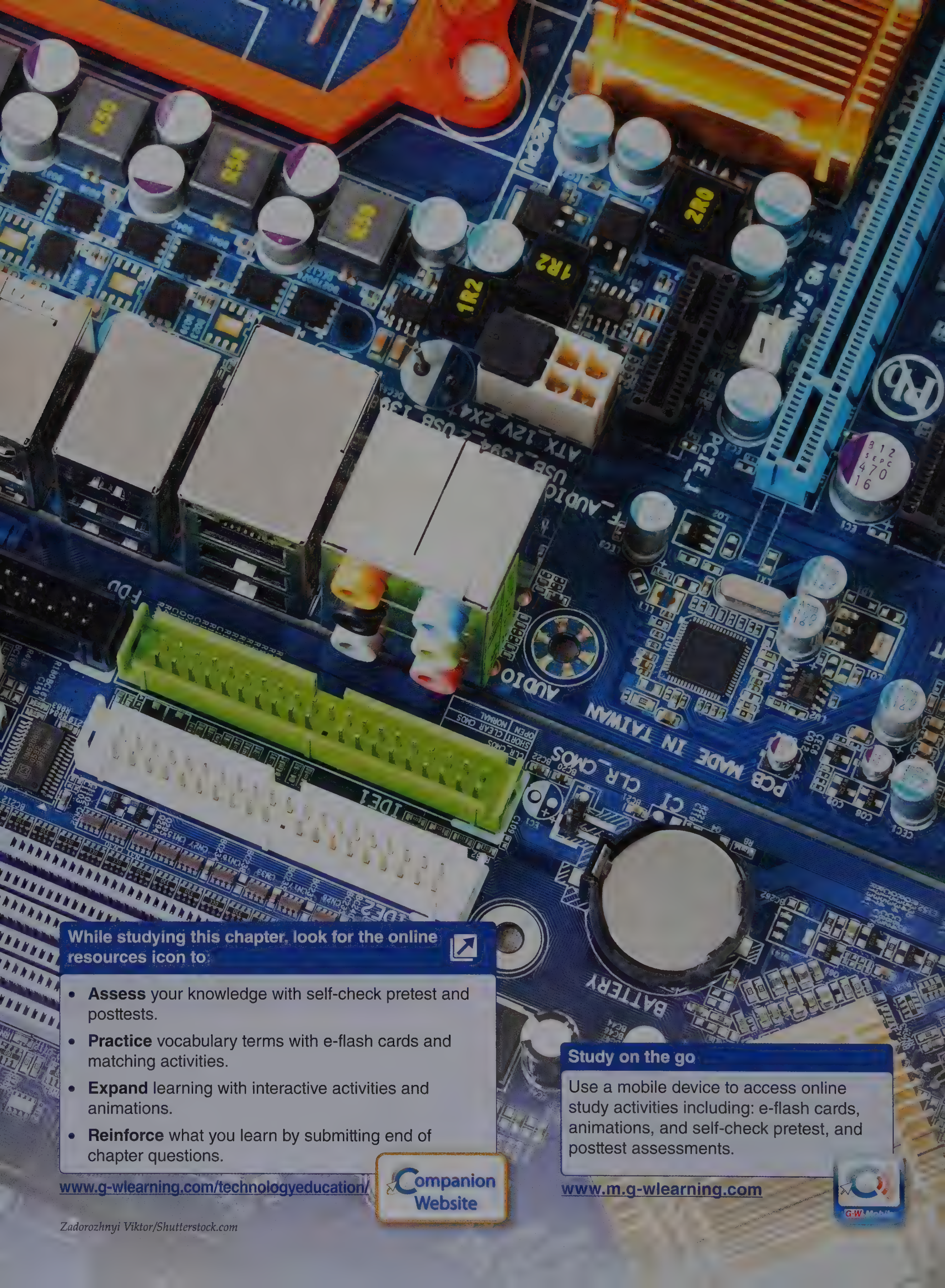
Assess *knowledge*

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is *bioengineering*?
2. Define *biotechnology*.
3. What are the three main areas of bioengineering?
4. _____ is the study of cell structures.
5. In the _____ selection method of evolutionary biology, farmers have the ability to help develop animals and crops that fit specific characteristics.
6. In a strand of DNA, the base guanine bonds with _____.
   A. adenine
   B. cytosine
   C. thymine
   D. uracil
7. The ability of an organism to regulate itself in order to maintain a constant state is _____.
8. How is energy stored in most organisms?
9. List and describe the two types of biomass conversion.
10. Which type of bioconversion process is typically conducted in tanks in order to produce methane?
11. What is the difference between pyrolysis and gasification?
12. What is a genetically engineered crop?
13. What is cloning?
14. Describe the work of monoclonal antibodies.
15. What types of materials are commonly used to determine DNA fingerprint?

Reinforce *learning*



While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
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Chapter 12

Computer Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *computer engineering*.
- Explain the operation of logic gates.
- Understand the purpose of databases.
- Describe the uses of algorithms.
- Describe the function of basic parts of a personal computer.
- Understand binary code.
- Give examples of computer engineering applications.

Key Terms

algorithm
AND gate
autonomous robot
binary code
computer-aided design (CAD) software
computer-aided manufacturing (CAM) software
computer-aided process planning (CAPP)
computer architecture
computer engineering
computer-integrated manufacturing (CIM)
database
digital signal processing
end-of-arm tooling
human-computer interaction (HCI)
logic
NAND gate
NOR gate
NOT gate
OR gate
robot
software engineering
XNOR gate
XOR gate

Practice vocabulary

Have you ever wondered who makes it possible for you to see the world through your computer, play video games and communicate online with people halfway around the world, or stay in constant communication using a cell phone? Have you ever wondered who develops the computer chips and software? You can be sure that you have computer engineers to thank for all of those things.

There are numerous engineering disciplines that work closely with and even overlap computer engineering. In this chapter, we will discuss robotics and computer numerical control as applications of computer engineering.

Electrical engineers design, manage, and troubleshoot electrical systems from power plants to electronic gadgets. Software engineers design and create software and often work closely with customers. ***Computer engineering*** is a unique field that overlaps with both electrical engineering and includes software engineering and hardware engineering. See **Figure 12-1**.

Computer engineers can either stay in the technological side of the field or receive further training to move into the management side of the field.

Computer engineers sometimes work alone on projects but often work in teams with engineers from other disciplines or people outside the engineering field. Computer engineers might work with people from the automotive field to increase the effectiveness or reliability of antilock breaking systems for cars. They might work with a toy manufacturer to embed circuitry and software in a popular children's toy. Computer engineers enjoy a great deal of flexibility. They often split time between lab work and meeting with customers and other people.

Figure 12-1.

Computer engineers work with hardware and software to create digital devices.

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Professional Aspects

The requirement for an entry-level computer engineer is a bachelor's degree in computer engineering, electrical engineering, computer science, hardware engineering, or other related fields. Internships are highly recommended as a way to gain entry-level positions. The strongest candidates have extensive experience with computers and software well beyond the classroom. For higher-level positions, master's degrees or doctorate degrees are usually required. To earn a degree in computer engineering or a related field, courses must be taken in programming, software development, networking, electrical engineering, general education, and more. In order to be accepted into computer engineering programs, high school students should earn the best possible grades in the highest-level math and science classes they can take. Taking high school computer courses shows an interest in and dedication to these subjects.

Many colleges and universities offer two-year associate's degree programs in computer engineering technology. These degrees prepare graduates for careers in the repair, maintenance, and installation of hardware and software.

Software engineers often start with a bachelor's degree in computer science. They must understand how to operate computers, write programs, and troubleshoot software and systems. Software engineers must be able to design software that meets people's needs and that they want to use. They write and troubleshoot extremely complicated software and make it simple for people to use and understand. They must also communicate with customers and with people in their own organizations. The field of software engineering is challenging, but the field is expected to grow.

The broadest professional society for computer engineers is the Institute of Electrical and Electronics Engineers (IEEE), with more than 375,000 members in more than 160 countries. There are other professional societies that support computer engineering, but IEEE is the largest. The Association for Computing Machinery, with over 100,000 members, is the largest professional association that deals with computing.

Computer Engineering Principles

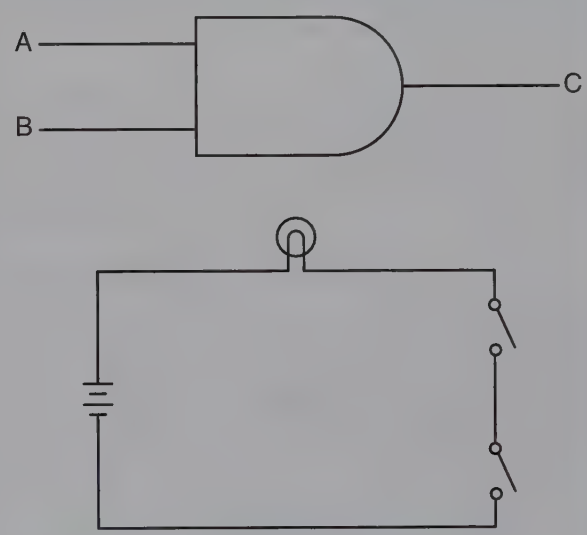
There are many principles that computer engineers must understand in order to design and troubleshoot computer systems. They need a strong background in electricity, electronics, electrical components, Ohm's law, and much more as discussed in Chapter 8. Computer engineers also need to be versed in computer architecture, logic, databases, and algorithms. Computer engineers can also concentrate on software design.

Logic

Logic refers to the system of operations performed by a computer. Computers are designed to break down problems or decisions into simple sets of logical decisions or reactions to situations. You may have heard the expression "if this, then that." For example, your teacher may say, "If you contribute to a class discussion, then you will earn extra points." These decisions are made in digital electronics using logic gates. Logic gates are usually implemented digitally through the use of diodes and transistors, which are often included in integrated circuits. An integrated circuit (IC) consists of multiple electronic circuits etched into a thin layer of silicon and enclosed in a protective material, such as plastic. Logic gates can also be implemented through the use of relays and other devices. Computer engineers must understand logic so they can understand, design, and troubleshoot systems that use logic.

The simplest logic gates are AND, OR, and NOT. These can be combined to create NAND and NOR gates. XOR and XNOR gates are a bit more complex and will be described later. Inputs and outputs are either high (1) or low (0). An output of high indicates on. An output of 1 would mean that the circuit has turned on.

AND gates provide an output of 1 only if both inputs (A and B) are 1. If both inputs are 0 or only one of the inputs is 0, then the output is also 0. Notice the example in **Figure 12-2**. Both switches must be closed (on) in order for the light to turn on. Maybe your parents are deciding if you may go out on Friday night. You may go if you clean your room AND wash the dishes. You would have to do both in order to go out.



Input Signal		Output Signal
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

Figure 12-2. Expand learning

Note the symbol for an AND gate. The switching circuit is used to simulate an AND gate. Note that both switches must be closed to power the light. The truth table shows the combinations of input signals to reach output signals.

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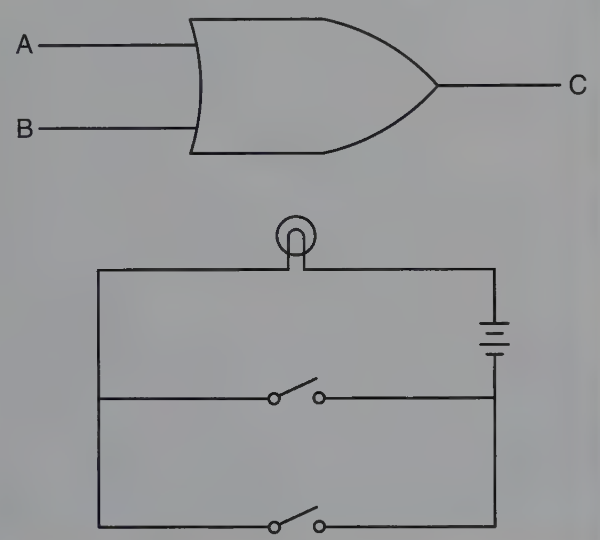
OR gates provide an output of 1 if either or both of their inputs are 1. See **Figure 12-3**. If both inputs are 0, then the output is also 0. In the mechanical example, there are two switches in parallel. One or both switches must be closed in order for the light to turn on. You may go out on Friday night if you either clean your room OR wash the dishes. You may also go out on Friday night if you do both.

NOT gates have only one input and one output. See **Figure 12-4**. They are called inverters because they change the input. If the input is 1, then the output is 0. If the input is 0, then the output is 1. Imagine your coach tells you that you need to win the game Friday night (1), or you will have to run extra laps on Monday at practice (also 1).



Input Signal		Output Signal
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

Figure 12-3. *Expand learning*

Note the symbol for an OR gate. On the sample circuit, note that closing either or both switches will power the light. The truth table shows the combinations of input signals to reach output signals.

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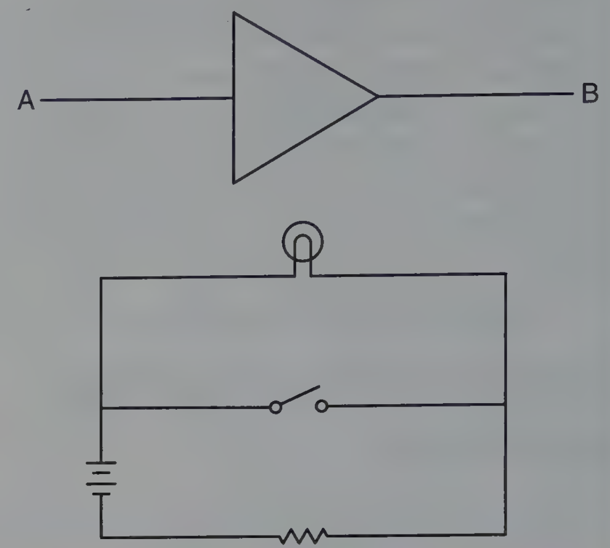

Input Signal	Output Signal
A	B
0	1
1	0

Figure 12-4. *Expand learning*

Note the symbol for a NOT gate. Notice on the sample circuit that when the switch is closed, the light is off. The truth table shows the combinations of input signals to reach output signals.

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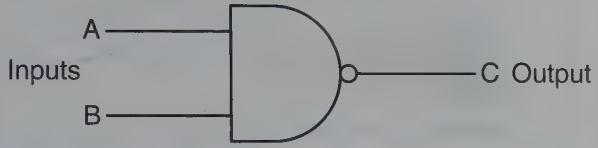
If you win the game, the input is 1, and the output is 0 (no running). If you lose the game, the input is 0, and the output is 1 (extra running). The mechanical example in **Figure 12-4** involves a relay. If there is power in the circuit, the relay pulls the switch open and the power turns off. If there is no power in the circuit, the switch remains closed. In this way, the circuit creates the reverse of what was applied.

All of the following gates are combinations of the basic AND, OR, and NOT gates.

NAND gates are a combination of NOT and AND gates. NAND gates are negative gates. The results of the NAND gate are opposite of the AND gate. If either or both inputs are 1, then the output is 0. If the inputs are both 1, then the output is 0. See **Figure 12-5**.



Input Signal		Output Signal
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

Figure 12-5.

Note the symbol for a NAND gate. The truth table shows the combinations of input signals to reach output signals.

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NOR gates give the opposite result of OR gates because NOR gates are made up of an OR gate and a NOT gate. If both inputs are 0, the output is 1. If either or both inputs are 1, then the output is 0. See **Figure 12-6**.

XOR gates are exclusive OR gates. Remember that OR gates provide an output of 1 if either or both inputs are 1. XOR gates only provide an output of 1 if one input is 1 but not if both are 1. See **Figure 12-7**.

Input Signal		Output Signal
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

Figure 12-6.

Note the symbol for a NOR gate. The truth table shows the combinations of input signals to reach output signals.

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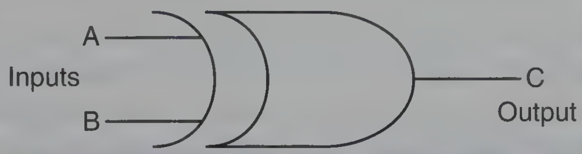

Input Signal		Output Signal
A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

Figure 12-7.

Note the symbol for an XOR gate. The truth table shows the combinations of input signals to reach output signals.

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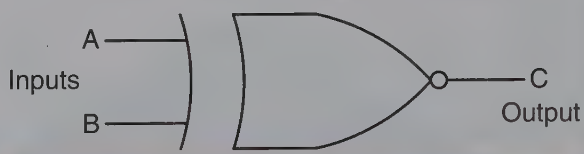
XNOR gates are exclusive NOR gates. They provide an output of 1 if the inputs are both 1 or both 0, but not if one is 0 and one is 1. See **Figure 12-8**.

Databases

A ***database*** is a structured system of storing data in a computer system. Think of your grades at school. Most schools now store all grades on computers. As you turn in your work, your



Input Signal		Output Signal
A	B	C
0	0	1
0	1	0
1	0	0
1	1	1

Figure 12-8.

Note the symbol for an XNOR gate. The truth table shows the combinations of input signals to reach output signals.

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teacher grades your work and puts your grades into a database. This database is a school-wide computer system for storing and managing grades. Teachers and administrators can then use this information to generate report cards, send home warnings for students with poor grades, and create reports that can be used to increase the quality of instruction. A school database is one example of how databases can be used to store and manage large amounts of information.

Databases must be easily accessible to people who need the information and also secure it from people who should not have access. Computer engineers design databases to meet the specific needs of the people who will use them. They can design the hardware and software that make the database possible, and they make sure the hardware and software function properly. Hardware in this case refers to the servers on which information is stored. Servers are computers dedicated to specific functions. In the case of a server, the physical computer is used to store information and make it accessible to people who have permission to access it. People use software to access the information on the server. The software is designed to make access as convenient as possible.

Algorithms

Algorithms are step-by-step procedures for solving problems or completing tasks. Many computer programs are designed using algorithms. Algorithms can be used to analyze data, manage information on databases, drive search engines, filter spam in your e-mail, operate "smart" traffic lights, and complete many other tasks.

A good example of an algorithm is the troubleshooting process you might use to figure out why a flashlight does not work. See **Figure 12-9**. The first step could be to check if the batteries are good. If the answer is no, replace the batteries. If the answer is yes, check to see if the bulb is burned out. If yes, replace the bulb. If no, replace the flashlight.

Of course, algorithms in computer software are usually much more complex. A simple example could be finding the area of a square.

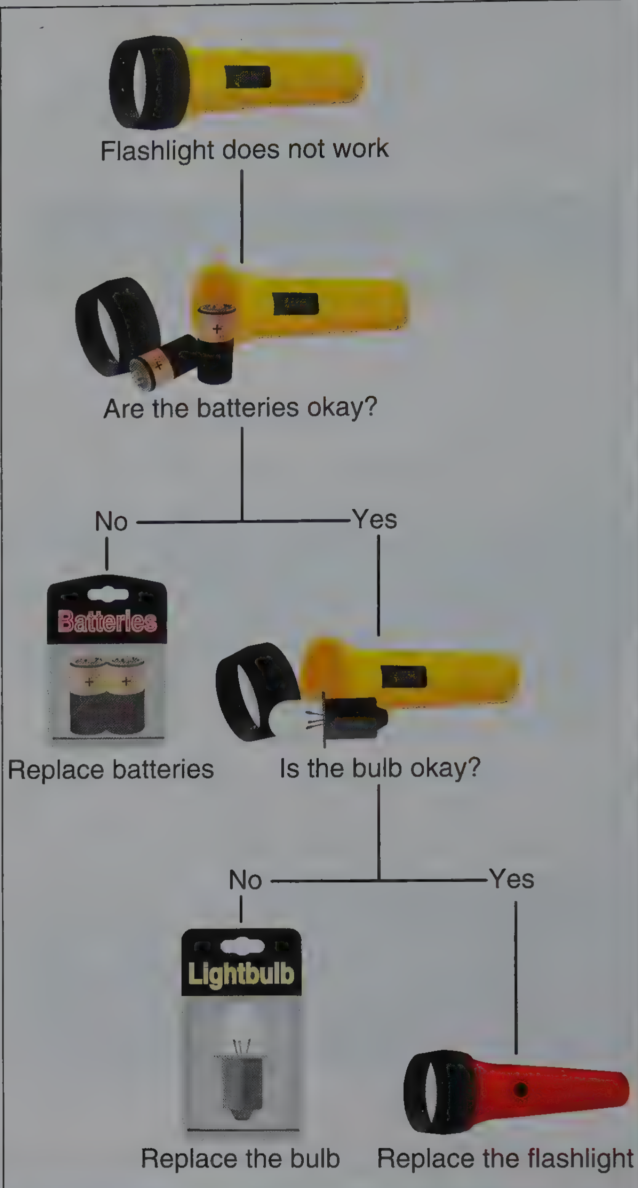

Figure 12-9.

Troubleshooting a flashlight is one example of an algorithm.

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This algorithm might look like this:

1. Ask for length of a side
2. Store length of side as s
3. Calculate area of the square (s × s)
4. Store the area of the square as a
5. Print a
6. Stop

Using this algorithm, you only have to input the length of one side, and the algorithm calculates the area of the square for you.

Computer Architecture

Computer architecture refers to the way in which computers are designed, with a focus on the central processing unit (CPU) and how it functions internally and accesses memory. Instruction set architecture (ISA) deals with programming. Microarchitecture deals with the parts of the computer and how they are connected to allow for ISA. System design covers all other hardware components.

To understand computer architecture, it is important to have a basic understanding of how computers operate. In this section, we will discuss the basic components of personal computers (PCs) and how they work.

The central processing unit (CPU) performs all the functions of the computer. It interprets and executes the commands. In modern computers, the CPU is made up on a single integrated circuit called the microprocessor. See **Figure 12-10**. Microprocessors are the heart of any personal computer and are located on the motherboard. The job of the CPU is to execute programs.

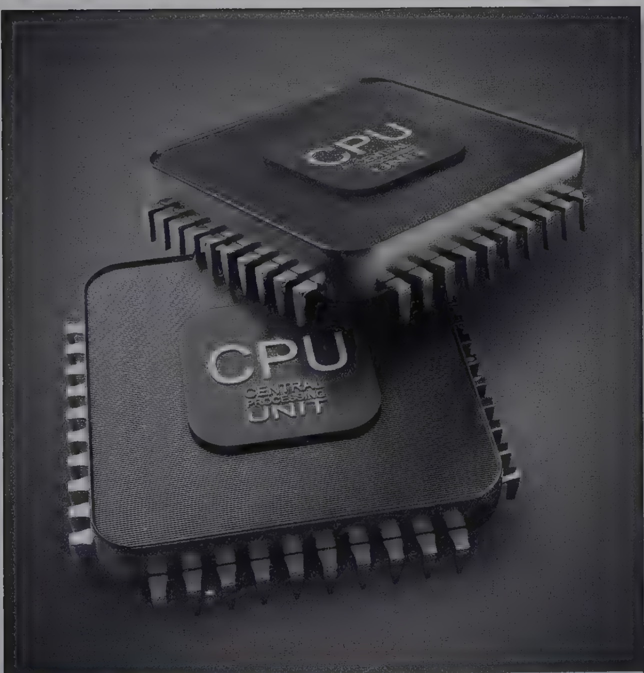

Figure 12-10.

Microprocessors perform several computer functions and are the heart of any PC.

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The motherboard is the main circuit board to which all other components connect. The motherboard houses the CPU and other critical components.

Power supplies are built into computers and convert 120 volts of alternating current (ac), which is the standard in the United States, to lower voltage direct current (dc), which is required for computer components. Power supplies typically supply direct current for 3.3 volts dc and 5.5 volts dc for digital circuitry and 12 volts dc for mechanical devices like motors and fans.

The hard disc is used for storing data on rotating platters with magnetic surfaces. See **Figure 12-11**. As the discs rotate, read/write heads can either read the data on the discs or write new data. This data is not lost when power is disconnected. Data is managed by dividing these discs into very small segments. Data can also be stored on external drives, CDs, flash drives, solid-state drives, DVDs, and other devices.

Operating systems manage the operation of the computer. Operating systems allow the user to interact with the computer, allocate resources, and organize and control hardware and software. Operating systems can be updated over time to meet changing needs without having to replace the entire machine.

Figure 12-11.

The hard disc stores data on rotating platters. As these discs rotate, data can either be read or written.

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Computers use a variety of different types of memory in order to function at optimum levels. The most basic is read-only memory (ROM), which is stored on the ROM IC. ROM comes programmed on the device and cannot be changed, or it can only be changed through specific procedures. Firmware is software specific to the operation of a device and it is stored in the ROM IC. ROM is nonvolatile, meaning that it is not lost when the power is turned off. Basic input/output systems (BIOS), which is a kind of ROM, serves as an interface between the operating system and the major hardware components. Random-access memory (RAM) is used to temporarily store data on which the computer is currently working. RAM is volatile, meaning that data is lost when the power is turned off.

If your computer does not have sufficient RAM, it will perform slowly and will not be able to perform multiple functions at one time. When additional RAM is required to perform operations, the computer will automatically access virtual memory. Virtual memory is the use of the hard drive as RAM. Virtual memory works more slowly, but allows the computer to continue functioning. Caching is the storage of frequently used data for easy access in the future. Cache memory is similar to RAM, but it is faster and is stored in the processor. It is faster to access this information from cache memory than to wait for RAM.

Flash memory refers to a solid state memory device. Solid state means there are no moving parts. Flash memory is nonvolatile and can be erased and saved over and over again. Examples of devices that use flash memory include flash drives, digital cameras, MP3 players, and other mobile devices. Flash storage is gaining popularity in personal computers because of its reliability and because it uses less power and makes less noise than other devices.

Ports are connections where external devices can be plugged into your computer. For example, you might use the USB (universal serial bus) port to plug in your flash drive or mouse, a FireWire port to plug in a digital camera, or the audio port to plug in your headphones or earbuds. See **Figure 12-12**. On a desktop computer, the monitor and keyboard are also plugged into ports.

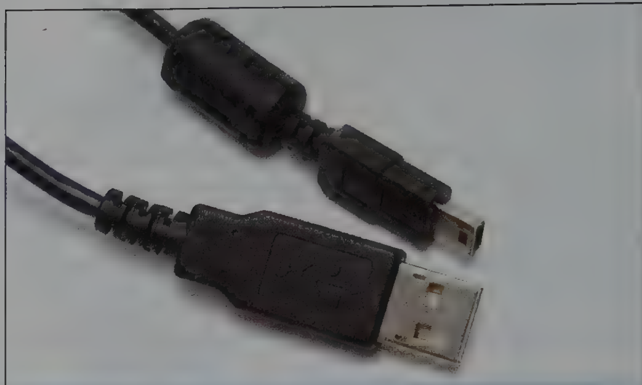

Figure 12-12.

USB and FireWire are the most common types of ports found on computers.

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Digital Signal Processing

Analog signals are transmitted using a series of sine waves. Digital signals are a series of 1s and 0s. Information is converted into a binary numeral system. The binary system is used in computers and other digital electronic devices because transistors and diodes understand only on and off. A 1 is on and a 0 is off. Therefore, numbers are converted into ***binary codes***.

How does binary code operate? The system of numbers you are accustomed to using is based on powers of 10. It looks like this:
(thousands) (hundreds) (tens) (ones)

Think of the number 1,256. You have 1 thousand, 2 hundreds, 5 tens, and 6 ones. This can be expressed as:

$$(1 \times 10^3) + (2 \times 10^2) + (5 \times 10^1) + (6 \times 10^0) = 1{,}256$$

So how can we convert decimal numbers to binary numbers? First we have to understand how binary numbers operate. They are all based on the number 2.

2 to the power of 0 $= 2^0 = 1$
2 to the power of 1 $= 2^1 = 2$
2 to the power of 2 $= 2^2$ or $2 \times 2 = 4$
2 to the power of 3 $= 2^3$ or $2 \times 2 \times 2 = 8$
2 to the power of 4 $= 2^4$ or $2 \times 2 \times 2 \times 2 = 16$
2 to the power of 5 $= 2^5$ or $2 \times 2 \times 2 \times 2 \times 2 = 32$
2 to the power of 6 $= 2^6$ or $2 \times 2 \times 2 \times 2 \times 2 \times 2 = 64$
2 to the power of 7 $= 2^7$ or $2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 128$
2 to the power of 8 $= 2^8$ or $2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 256$

Going Green

Green Computer Tips

With each passing year, businesses, schools, and people purchase and use computers. Knowing that computer use will only increase over time, many people are concerned with the energy computers consume. There are numerous conservation practices people can use to decrease the energy consumption of their computers at home, at school, and in the workplace.

First, the age and type of computer you use makes a big difference. Newer computers tend to use less energy than older computers. LCD monitors use much less energy than older style monitors. Laptops use less energy than desktops. Computers are now available with ENERGY STAR® ratings. The rating represents the efficiency of the components, the efficiency of the power supply, and the power conservation settings.

Beyond the computer you own, there are several things you can do to decrease the amount of energy your computer consumes. The simplest thing is to turn off your computer and peripheral devices when you are not using them. There are myths about shutting down computers. One says that it takes a surge of energy to start a computer, which negates the benefits of turning it off. Another myth is that repeatedly shutting down and restarting your computer will cause the computer to fail prematurely. Both of these are untrue. The best practice is to turn off your computer when you are not using it. However, computers and many other electronic devices still consume electricity even when they are shut down. These phantom loads can be avoided by plugging all electronic devices into power strips and switching off the power strips after the devices have been shut down. Instead of using power strips, you can simply unplug devices.

Figure A

Melinda Fawver/Shutterstock.com

Another way to decrease energy use is to adjust the settings. Keep in mind that screen savers were designed to save the screen and not to save energy. Running screen savers requires as much electricity as most computing operations. The best thing is to adjust the settings so the monitor goes to sleep after 20 minutes of inactivity and the system goes to sleep after 30 minutes. Once this is set, it happens automatically without you having to do anything.

When you replace a computer, do not throw the used computer in the trash. Computers that still have some value can be donated to and reused by schools, charities, and community groups. Computers that are of no use to anyone can be recycled. See **Figure A**. Materials from old electronics can be extracted and reused. Computers contain many hazardous materials as well. The recycling process extracts these materials and disposes of them in a safe manner.

Now we'll convert the number 87 to a binary number. Take the largest power of 2 that is less than 87 and subtract it out.

$87 - 64 = 23$

Then continue that process until you get to zero.

$23 - 16 = 7$
$7 - 4 = 3$
$3 - 2 = 1$
$1 - 1 = 0$

Math

Matrices

A matrix is an array of numbers. Matrices are commonly used in software engineering. Matrices can make it easier to use many numbers at one time. Do you use 3-D modeling software and change it from one view to another? Do you play video games that have depth and perspective? If so, you may not have known it, but you have used matrices. Matrices are simple and convenient ways to organize many numbers. Below is an example of a 3 × 2 matrix. It is called *three by two* because it has three rows and two columns.

$$\begin{bmatrix} 2 & 1 \\ 7 & 5 \\ 4 & 9 \end{bmatrix}$$

Matrices can be added and subtracted as long as the two matrices are the same size. The following is an example of adding matrices.

$$\begin{bmatrix} 2 & 1 \\ 7 & 5 \\ 4 & 9 \end{bmatrix} + \begin{bmatrix} 5 & 6 \\ 6 & 4 \\ 2 & 5 \end{bmatrix} = \begin{bmatrix} 7 & 7 \\ 13 & 9 \\ 6 & 14 \end{bmatrix}$$

The following is an example of subtracting matrices.

$$\begin{bmatrix} 2 & 1 \\ 7 & 5 \\ 4 & 9 \end{bmatrix} - \begin{bmatrix} 5 & 6 \\ 6 & 4 \\ 2 & 5 \end{bmatrix} = \begin{bmatrix} -3 & -5 \\ 1 & 1 \\ 2 & 4 \end{bmatrix}$$

The following is an example of multiplying an entire matrix by a number. Each number in the matrix is multiplied by the number, and the products are placed in the matrix.

$$\begin{bmatrix} 5 & 6 \\ 7 & 1 \\ 3 & 4 \\ 8 & 2 \end{bmatrix} \times 2 = \begin{bmatrix} 10 & 12 \\ 14 & 2 \\ 6 & 8 \\ 16 & 4 \end{bmatrix}$$

Add, subtract, and multiply the following matrices as directed.

1. $\begin{bmatrix} 1 & 12 \\ 3 & 4 \end{bmatrix} + \begin{bmatrix} 8 & 7 \\ 6 & 2 \end{bmatrix}$

2. $\begin{bmatrix} 16 & 8 \\ 18 & 7 \\ 13 & 5 \end{bmatrix} - \begin{bmatrix} 12 & 5 \\ 13 & 7 \\ 6 & 9 \end{bmatrix}$

3. $\begin{bmatrix} 6 & 8 \\ 9 & 1 \\ 7 & 13 \\ 15 & 5 \\ 12 & 2 \end{bmatrix} \times 3$

4. $\begin{bmatrix} 36 & 18 \\ 12 & 17 \\ 4 & 8 \\ 9 & 3 \end{bmatrix} + \begin{bmatrix} 27 & 9 \\ 56 & 13 \\ 12 & 14 \\ 8 & 12 \end{bmatrix}$

5. $\begin{bmatrix} 4 & 8 \\ 2 & 19 \end{bmatrix} \times 6$

6. $\begin{bmatrix} 16 & 14 \\ 22 & 33 \end{bmatrix} - \begin{bmatrix} 8 & 10 \\ 12 & 14 \end{bmatrix}$

We have used one 64, one 16, one 4, one 2, and one 1. In chart form we can show it like this:

64	32	16	8	4	2	1
1	0	1	0	1	1	1

1010111 = 64 + 16 + 4 + 2 + 1

We now know that 01010111 = 87.

Software Engineering

Software directs the operation of a computer. Software can come in the form of programs, web pages, video games, and anything else that is not hardware. ***Software engineering*** is the application of engineering principles to software design. It is a systematic, quantifiable approach to software development. Some see software development as an art, but engineers see it as a disciplined approach following the steps of the engineering design process. Most software is custom designed to meet a specific need. Writing software is similar to writing a set of instructions to perform any other task, such as changing a tire on a bike or baking a cake.

Computer Engineering Applications

Computer engineers work in a wide variety of fields, which may include designing new electronic devices, ensuring software compatibility with hardware, designing software, and designing whole computerized systems. Some of these topics are described below.

Human-Computer Interaction (HCI)

The study of the interactions between humans and computers is one of the fastest growing fields. ***Human-computer interaction (HCI)*** can describe anything from typing on your keyboard to playing a virtual reality football game. HCI is the place where computer science, behavioral science, ergonomics, and design meet. HCI takes place at the user interface, which is the point where a person deals with a computer. See **Figure 12-13**. It occurs at the input end where the user touches something like a keyboard or mouse.

Figure 12-13.
Human-computer interaction describes the user input at the keyboard as well as the output appearing on the user's screen.

Lisa S./Shutterstock.com

It also occurs at the output end where a user sees his or her work on the screen or hears it through a speaker.

HCI deals largely with user satisfaction. Computers are designed to maximize the experiences for users and minimize the time and effort required from users. HCI is designed to be ergonomic, meaning that computers are designed to meet the physical needs of users and minimize the fatigue and repetitive motion injuries that are often associated with extensive computer use. Software is also designed to maximize user satisfaction. Think of your favorite video game or social networking program. These things are all designed to make you enjoy using them. Think of the many ways in which you can interact with computers. You can use a keyboard, a mouse, a monitor, speakers, or a touch screen to input or receive information.

History

Computer Engineering in History

Steve Jobs, Steve Wozniak, and Ronald Wayne founded Apple Computer (now Apple Incorporated) in 1976. Wayne soon left the company. Apple is a hugely popular designer and manufacturer of consumer electronic devices, communication devices, software, and network solutions. Apple is a massive global corporation today, but it all started in a garage.

In 1971, Steve Jobs first met Steve Wozniak, and the two became friends. By 1975, Jobs was designing video games for Atari, and Wozniak was working as a computer engineer for Hewlett-Packard Company. In 1976, they quit their jobs and started Apple with the goal of making inexpensive personal computers that were easy to use.

Their first computer was the Apple I, which Wozniak designed, programmed, and then assembled in his garage. The Apple I was unique because, unlike other personal computers of the day, the circuit board came fully assembled. See **Figure A**. It only needed a keyboard, a power supply, a case, and a television set for the monitor. Other computer circuit boards came as kits that had to be assembled by the buyer.

Figure A.

Old Computer Museum

The Apple I was a huge success. Wozniak went on to design and write software for the Apple II with the goal of keeping the key characteristics of usability and simplicity. He also added high-resolution graphics, which allowed the user to display pictures rather than just numbers and letters. He then designed an inexpensive floppy disc drive.

Wozniak's disc drive was a testament to his abilities as a computer engineer. It amazed even his peers, who went on to say that Wozniak did not design his floppy drive based on how others had designed theirs, but that he thought about how it should be designed. His floppy drive was much smaller and had many fewer integrated circuits, but outperformed the others on the market.

Wozniak's talent for designing computers and writing software to run on them has made him one of the most successful and influential computer engineers in history.

Steve Jobs went on to cofound and become the CEO of NeXT, which was a computer design company. He later cofounded and became the CEO of Pixar Animation Studios. He went back to Apple as the CEO. He oversaw massive hardware and software development that included the iMac, iPods, iTunes, iPhones, and iPads. Steve Jobs was one of the greatest inventors, designers, and visionaries.

Computer-Integrated Manufacturing (CIM)

Computer-integrated manufacturing (CIM) is a manufacturing process where computers control the entire production process. See **Figure 12-14**. Parts are designed using ***computer-aided design (CAD) software*** and are often made using computer numerical control (CNC) equipment. ***Computer-aided process planning (CAPP)*** is used to design processes used to manufacture parts. Industrial robots are used to complete repetitive tasks, especially when high levels of quality and repeatability are required. Computer systems are integrated in this process, so there are no communication barriers in the process from design to production.

Computer Numerical Control (CNC)

Traditionally, highly skilled workers were needed to operate the manufacturing equipment used to make parts and products. The process of manually operating equipment was time consuming and expensive, as well as lacking in quality.

Computer numerical control (CNC) is the automation of machine tools using computers rather than manual devices. Parts are often designed and drawn using computer-aided design (CAD) software. CAD drawings are imported into ***computer-aided manufacturing (CAM) software***. In the CAM software, users input the type of material to be cut, the type and size of the cutter, the speed the cutter will move, and more. Cutting operations can even be seen in 3-D simulations before the parts are cut to see if there are any problems. CAD/CAM software allows people to design parts and see how the CNC machine will run remotely without interrupting the CNC machine. This allows for greater productivity. If problems are found in simulation, modifications can be made before the CNC machine is used.

CAM software creates the codes for machine movement. This code is sent to the CNC controller, which includes a power supply for the CNC machine, electrical safety protection, and motor drivers. The motor drivers interpret the code and determine when to turn on the butting tool and when to turn on the motors that control the movement of the machine. Imagine the program called for a CNC router to move across the part and drill a hole. The controller would send out electricity to turn on the stepper motors that control horizontal movement until the router was over the location. It would then turn those motors

Figure 12-14. Computers control the entire production process in computer-integrated manufacturing.

Baloncici/Shutterstock.com

off and turn on the motor that moves the router down until the desired hole depth was reached. The machine would likely reverse these steps to return the router to its original position.

CNC systems can be used to control all types of equipment, including routers, turning centers, machining centers, laser cutters, plasma cutters, water jet cutters, and electrical discharge machines (EDMs). See **Figure 12-15**. CNC routers are commonly used for engraving designs and cutting out shapes. Turning centers are CNC lathes, which are used to cut threads, knurls, and other shapes into stock as the stock rotates. Threads are the spiral-shaped grooves on the outside of bolts and on the inside of nuts that allow them to screw together. Knurling is the process of imprinting a pattern on the material by pressing a very hard roller with a pattern against a rotating surface. Think of the pattern on the outside of a metal flashlight or the ridges on the outside edge of a quarter. Machining centers are CNC mills. Tools are often stored in the machines and can be changed when necessary so a complete part can be made without stopping the machining process. CNC lasers use a high-density light beam to cut materials like wood, plastic, and metal.

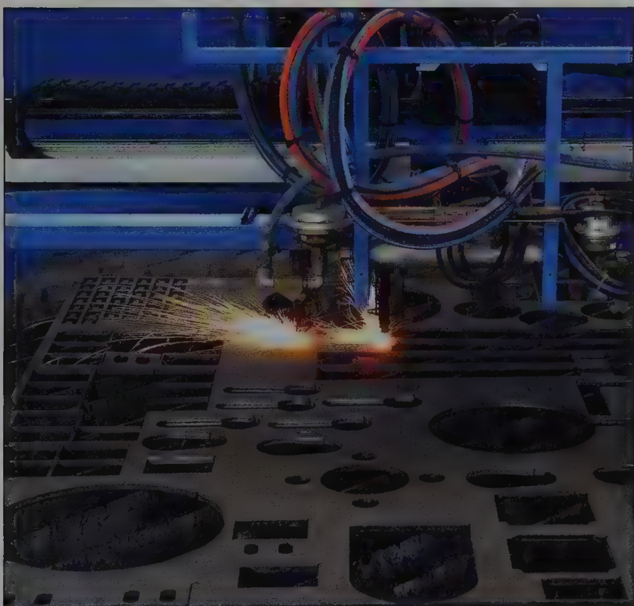

Figure 12-15.

Electrical discharge machines controlled by CNC systems can be used to make accurate cuts on parts.

Mircea BEZERGHEANU/Shutterstock.com

CNC plasma cutters send an electrical arc through gas escaping through a small nozzle. This causes the gas to enter the fourth state of matter, plasma. The high-speed gas cuts the molten metal. Plasma cutters are accurate compared to traditional metal cutting methods. CNC water jet cutters use high-speed water jets filled with grit to cut materials. CNC electrical discharge machines (EDMs) use rapid discharges of electricity to cut through materials. Regardless of what kind of manufacturing device employs CNC technology, parts are made faster, more efficiently, and of higher quality.

Highly skilled workers design parts and set up CNC machines for use. Less skilled workers can then operate CNC equipment, thereby saving labor costs. Computer engineers might design the hardware and software required for the entire process and make sure it operates correctly.

Robotics

Robots are automatically controlled, reprogrammable, multipurpose machines. In manufacturing, they are most commonly found in the form of robotic arms, which are used in assembly lines and for other operations.

Think of an automobile assembly line. See **Figure 12-16**. Robots put parts into place, weld parts together, spray paint, and perform many

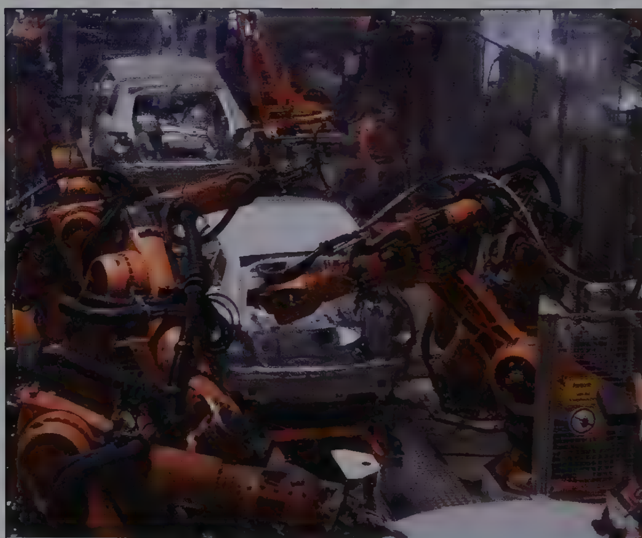

Figure 12-16.

A common example of using robots is in an automobile assembly line.

Small Town Studio/Shutterstock.com

other operations. Robots can achieve higher accuracy rates than humans and can perform activities that could be dangerous for humans, such as heavy lifting. The accuracy of robots is particularly valuable in the manufacture of integrated circuits, which can contain billions of electronic components on a small slice of semiconductor material (usually silicon).

Robots are operated by computers, which control manipulation, sensing, intelligence, and data processing. Manipulation is the control of the robot movement—its speed and path. Sensing gathers information from the work being done. Intelligence uses the gathered information to modify operations where necessary. Data processing is the capability to communicate with other machines, keep records, generate reports, and control activity.

While initial startup costs are high for the use of robots in manufacturing systems, the use of robots over the long term decreases labor costs, increases production, and improves quality. Because of the startup costs, robots are most economical for high-volume, continuous manufacturing operations.

Common robotic arms comprise seven metal pieces connected by six rotational joints. This is called six degrees of freedom. The rotation of the joints is controlled by step motors. Step motors move in exact increments controlled by the computer.

Robotic arms closely resemble human arms. They have an equivalent to a shoulder, an elbow, and a wrist. Your shoulder is connected to your body. Robot shoulders are connected to either fixed or mobile bases. The job of the arm is to put the hand in the correct place to perform a task. The movements are broken down into position movements and orientations. Position movements are arm sweep, shoulder swivel, and elbow extension. Orientation movements deal with the wrist at the end of the arm. They are pitch, yaw, and roll. See **Figure 12-17**.

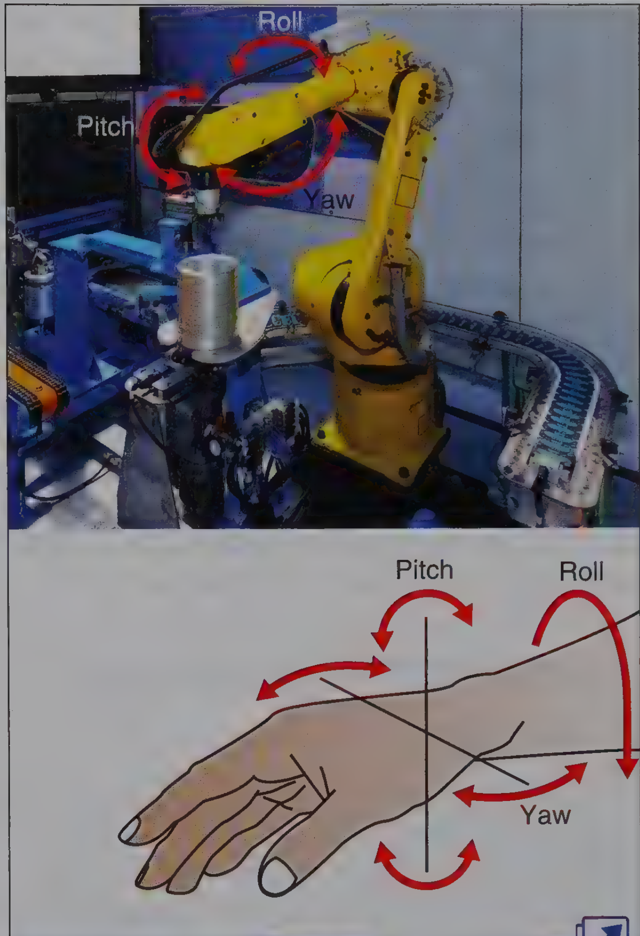

Figure 12-17. Expand learning

Robotic arms are similar to human arms and hands and have six degrees of freedom.

Baloncici/Shutterstock.com; Goodheart-Willcox Publisher

End-of-arm tooling means a tool can be attached to the tool plate on the end of the arm. The most common form of end-of-arm tooling is grippers. Grippers can be mechanical like your hands. These grippers often use sensors to determine how tightly they should grip so they do not crush or drop parts. Vacuum grippers use suction cups to lift things like windshields, body panels, and boxes. Magnetic grippers are also used. End-of-arm tooling can also include things like paint sprayers, drills, grinders, welders, and other tools.

While robotic arms are the most common robots in manufacturing, robots have many other uses. Robots are often used to explore areas that are too dangerous for humans. For example, they can be used to search for and neutralize bombs. Robots have been sent as far away as Mars. They explore the surface, collect and analyze samples, and send information back to Earth.

More advanced robots are autonomous. ***Autonomous robots*** are programmed to respond to the world around them. Rather than following specific programs to perform given tasks, they analyze their surroundings and adapt.

A rover dropped on Mars might analyze the terrain in front of it. See **Figure 12-18**. If the terrain is too rough for travel, it might calculate another path to take.

Integrated Circuits (ICs)

As discussed in Chapter 8, integrated circuits (ICs) are the combination of many semiconductors and other components manufactured into the surface of semiconductor material. Each IC is designed to perform a specific function or variety of functions. The invention of ICs revolutionized electronics because ICs allowed electronic devices to become smaller and use less energy to operate. Computer engineers are often responsible for designing ICs for specific applications.

Computer Engineering in Action

Computer engineers often work to design software and hardware that work seamlessly together for the benefit of the user. Think of a smartphone. The hardware (physical part of the phone) and the software have to be designed together so they function in a way that meets the needs of the user.

Design

Integrated Circuit Design

An integrated circuit (IC) consists of multiple electronic circuits that are etched into a thin layer of material and enclosed. ICs are not typically designed and drawn at a 1:1 scale. Because integrated circuits are small and contain many components, they are drawn much larger so all the details are easily seen by the engineers. Before manufacturing ICs, the design is reduced to the size of the actual IC.

Today's ICs can contain billions of different components, so it is important to find a way to include them in the design and to make them easy to see. Integrated circuits can be drawn in layers to help differentiate between types of components and circuit pathways.

Integrated circuits are also drawn much larger to ensure certain parts of the design do not touch or interfere with other components of the circuit. If certain parts, pathways, or components within the circuit were to touch, there could be a short within the circuit.

Figure 12-18.
The NASA All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE) is a six-legged robot that is currently under development for future missions.

NASA

Virtual Reality

Virtual reality is an example of a product of computer engineering. Virtual reality allows users to interact with a computer simulated environment. This environment could be fictional (in the case of a video game) or real (in a medical application).

Most virtual reality applications are predominantly visual. They provide the illusion of depth by showing a slightly different image to each eye. Sound is often provided to increase the sensation. Virtual reality that takes the form of sight and sound can provide great experience to gamers and in the area of training and simulation. See **Figure 12-19**.

The next step in virtual reality is in haptics, which is the science and physiology of touch. In virtual reality, haptics provides feedback to the user through the user's sense of touch. You might be familiar with haptics in video games. Steering wheels in video games often resist turns or slip to simulate what a real driver feels. Imagine a surgeon learning how to operate on people using a virtual reality program with haptics. The surgeon could "feel" what it is like to make an incision.

When most students think of virtual reality, they think of gaming applications. Virtual reality can certainly make gaming more enjoyable and realistic for the players. But virtual reality is a valuable tool in other areas as well. Would you want a doctor performing a surgery on you or one of your family members if it was their first time? Virtual reality can be used to train doctors for surgery in much the same way that flight simulators have been used to train pilots for years. Virtual reality can also be used to train drivers, equipment and machine operators, and astronauts. The technology is not yet readily available for many of these applications, but it is growing closer each day.

Figure 12-19.

The sight and sound of gaming can be enhanced through virtual reality.

Leah-Anne Thompson/Shutterstock.com

Medical Imaging

CT scans and MRIs are used by doctors to create images of the insides of people's bodies. Doctors then study these pictures to determine treatment options. Technology is available to take two-dimensional pictures and create three-dimensional images on computer screens. Using tools similar to video game controllers, doctors can navigate through these three-dimensional images to look around inside patients' bodies. See **Figure 12-20**. These tools can add things like radiation beams to see exactly where they will go inside the body for cancer treatment. As this technology becomes more widely used, diagnosis and treatment will certainly improve.

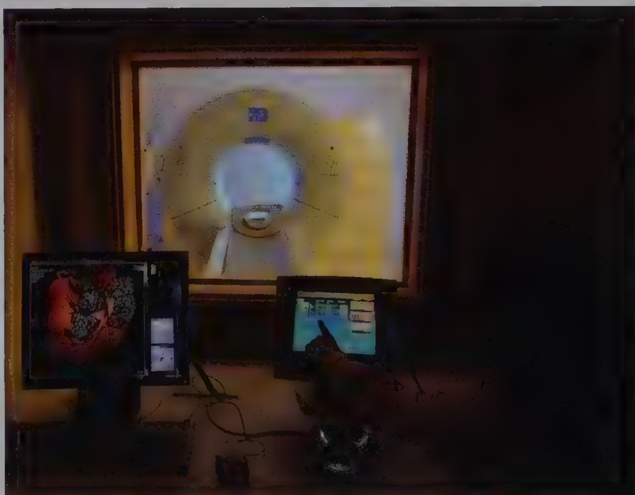

Figure 12-20.

This MRI machine as seen from the control room. Results are shown on the monitors.

Levent Konuk /Shutterstock.com

Summary

- Computer engineers share much of the same knowledge and skills as electrical engineers and software engineers.
- To earn a degree in computer engineering or a related field, courses must be taken in programming, software development, networking, electrical engineering, and general education.
- To make decisions in digital electronics, logic gates are used. Logic gates are usually implemented through the use of diodes and transistors.
- Databases are designed to store information. They must also be easily accessible to users while being secure from people who should not have access.
- Algorithms are used to design computer programs in addition to completing other tasks.
- Computer architecture focuses on the physical design of the computer, while instruction set architecture focuses on computer programming. All personal computers, regardless of their manufacturer or operating system, function in the same basic way.
- Digital electronic devices convert numbers into binary codes because digital signals only understand on and off. A 1 is on and a 0 is off.
- Human-computer interaction includes any input by the user and any feedback to the user from the computer.
- Computer-integrated manufacturing (CIM) uses computers to automate the entire production process.
- Computer numerical control (CNC) allows parts to be made faster, more efficiently, and of higher quality.
- Robots are commonly used in assembly lines and other operations. Robotic end-of-arm tooling allows for flexibility in a robot's purpose. More advanced robots can respond to the world around them.
- The invention of the integrated circuit (IC) revolutionized electronics because ICs allowed electronic devices to become smaller and use less energy to operate.
- Software engineering is the application of engineering principles to software.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is *computer engineering*?
2. What level of education is required to become a computer engineer?
3. A(n) _____ gate provides an output of 1 if either or both inputs are 1.
   A. AND
   B. OR
   C. NOT
   D. NAND
4. A(n) _____ gate provides an output of 1 if both inputs are 0. If one or both inputs are 1, the output is 0. If the inputs are both 1, the output is 0.
   A. AND
   B. OR
   C. NOT
   D. NAND
5. A(n) _____ gate provides an output of 1 only if both inputs are 1.
   A. AND
   B. OR
   C. NOT
   D. NAND

6. A(n) _____ gate provides an output of 1 if the inputs are both 0 or both 1, but not if one is 0 and one is 1.
   A. NAND
   B. NOR
   C. XOR
   D. XNOR
7. A(n) _____ is a system for storing data in a computer system.
8. Many computer programs are designed using _____, which are step-by-step procedures for solving problems or completing tasks.
9. _____ are the heart of any PC and are located on the motherboard.
   A. CPUs
   B. Microprocessors
   C. Programs
   D. Operating systems
10. Which type of memory stores frequently used data for quick access?
    A. ROM.
    B. RAM.
    C. Cache.
    D. Virtual memory.
11. Which type of memory is programmed at the factory?
    A. ROM.
    B. RAM.
    C. Cache.
    D. Virtual memory.
12. Which type of memory is used to temporarily store data on which the computer is currently working?
    A. Flash memory.
    B. RAM.
    C. Cache.
    D. Virtual memory.
13. What type of port is typically used with flash drives?
14. What is the difference between decimal numbers and binary numbers?
15. Computer science, behavioral science, ergonomics, and design all merge in the study of _____.
    A. digital signal processing
    B. human-computer interaction
    C. computer numerical control
    D. computer-integrated manufacturing
16. The process where machine tools are driven by computers rather than by manual devices is _____.
17. _____ use rapid discharges of electricity to cut through materials.
18. Automatically controlled, reprogrammable, multipurpose machines used in manufacturing are called _____.
19. _____ are the combination of many semiconductors and other components manufactured into the surface of semiconductor material.
20. _____ is the science and physiology of touch, providing feedback to users through the sense of touch.

Reinforce learning

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

www.g-wlearning.com/technologyeducation/

Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 13

Aerospace Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *aerospace engineering*.
- Explain Newton's laws of motion.
- Explain the roles of fluid mechanics and aerodynamics in aerospace engineering.
- Understand the laws of conservation.
- Describe the forces acting on an aircraft in flight.
- Give examples of aerospace engineering applications.

Key Terms

aerodynamics
aeronautics
aerospace engineering
aileron
angle of attack
angle of incidence
astronautics
Bernoulli theory of lift
dihedral angle
drag
elevator
flap
gas turbine engine
lift
pitch
propeller
propulsion system
rudder
satellite
thrust
wind turbine
yaw

Practice vocabulary

Aerospace engineers work in all aspects of aeronautics (aircraft) and astronautics (spacecraft). ***Aerospace engineering*** is the designing, building, analyzing, and troubleshooting of components of aircraft, spacecraft, missiles, and high-altitude vehicles. Aerospace engineers are involved with guidance and control systems, space exploration, instrumentation, navigation, and much more. See **Figure 13-1**.

The field of aerospace engineering is made up of two smaller, more focused engineering disciples. Aeronautical engineering deals with aircraft that operate within the earth's atmosphere, while astronautical engineering deals with craft that operate outside the earth's atmosphere.

Professional Aspects

The requirement for an entry-level aerospace engineer is a bachelor's degree in aerospace engineering. For higher-level positions, master's degrees or doctorate degrees are usually required. In order to be accepted into an engineering program, students need good grades in high-level secondary math and science classes. Students should plan to take a minimum of one year of biology, one year of chemistry, one year of physics, and math through calculus.

Many colleges and universities offer two-year associate's degree programs in aerospace engineering or aerospace engineering technology. These degrees can lead into four-year programs or qualify graduates for jobs as aerospace technicians. Aerospace technicians typically work in the manufacture or maintenance of aircraft and spacecraft.

The largest professional society for aerospace engineering is the American Institute of Aeronautics and Astronautics (AIAA). Despite its name, the AIAA is an international organization with over 31,000 members around the world. The AIAA holds conferences all over the world and publishes professional journals.

Most aerospace engineers are employed in the aircraft industry working for companies that make aircraft, parts of aircraft, and military equipment. Many are employed by the US Department of Defense, the National Aeronautics and Space Administration (NASA), and private space companies.

Figure 13-1.
Aerospace engineers design, build, analyze, and troubleshoot components in the fields of both aeronautics and astronautics.

perspectivestock/Shutterstock.com; Jose Antonio Perez/Shutterstock.com

Aerospace Engineering Principles

The following sections describe many of the principles you will need to know in order to work on projects and coursework related to aerospace engineering. You will learn about the principles of flight as well as the laws that describe the principles of flight.

Newton's Laws

Sir Isaac Newton is arguably the most influential scientist and mathematician in history. He was born in England in 1642. He defined laws of motion and universal gravitation. He was the first to accurately predict the exact movement of stars and planets. His laws of motion have had a tremendous impact on aerospace engineering.

Newton's First Law of Motion

"Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it."

Newton's first law is commonly referred to as the law of inertia. Simply stated, objects at rest tend to stay at rest, and objects in motion tend to stay in motion unless acted on by outside forces. For example, a stationary soccer ball on a flat surface will remain stationary until it is acted on by an outside force, such as a person kicking it. Think of yourself riding a skateboard and one of your wheels hits a rock, stopping the skateboard. The skateboard stops and you continue forward.

Newton's Second Law of Motion

"Force is equal to the change in momentum per change in time. For a constant mass, force equals mass times acceleration."

Newton's second law is particularly important because it provides a mathematical relationship between mass and acceleration. Mass is the amount of material in an object, which is commonly measured in kilograms. Acceleration is any change in velocity (speed) of an object. The velocity of an object changes when a force is applied. The reverse is also true. A force is created when velocity changes. The force of a foot kicking a soccer ball changes the ball's velocity. The kicking action that changes the velocity of the ball creates force acting on the foot. In aircraft, as air flows around a wing, the air is turned downward. The wing creates a downward force on the air, which in turn creates an upward force on the wing (lift). See **Figure 13-2**.

For an object with constant mass, force (F) can be calculated by multiplying mass (m) by acceleration (a). This can be shown as:

$$F = m \times a$$

Think of pulling a wagon that has 10 kg of mass with a force of 100 newtons (about 22.5 lb).

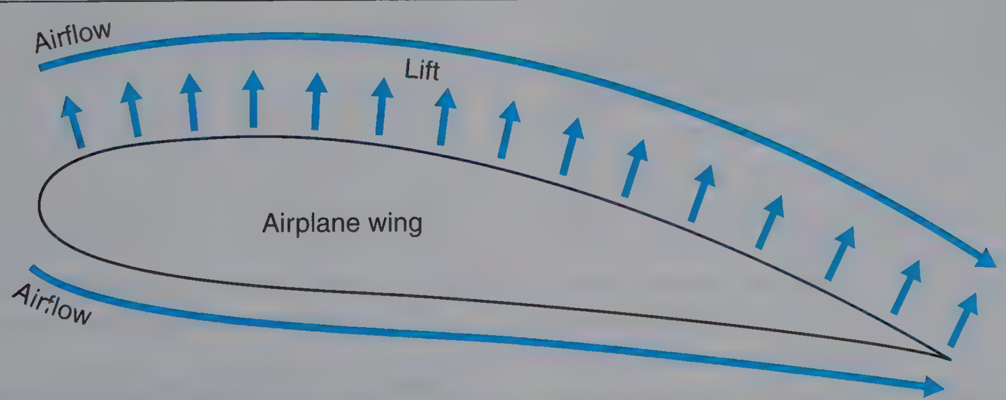

Figure 13-2.

Newton's second law explains how the downward force on a wing can also create the upward force of lift.

Goodheart-Willcox Publisher

Mass, Weight, and Gravity

When you weigh an object, what is the information you learn? You probably think you are learning the object's weight, but you are also learning its mass. Mass is the amount of matter of an object. When you think about something being weightless in space, this does not mean the object in space has no mass. An object's mass remains the same regardless of gravity. Mass can be measured in ounces, pounds, grams, and kilograms.

In physics, the term *weight* actually refers to the gravitational force on an object. Because weight is a force, it is measured in newtons. Gravity is the attraction between objects of mass. Earth, as a large object of mass, has a specific gravitational acceleration, which is about 9.81 m/s^2. Other large objects of mass have different values for gravity. For example, the moon has a gravitational acceleration of about 1.6 m/s^2.

Because large objects of mass have different values for gravity, the weight of an object is not constant. The weight of an object will change depending on gravity. For example, an object's mass will remain the same on earth or in space, but the object's weight will be different because the force, or gravity, acting on the object varies.

You can find the acceleration of the wagon using the following formula:

$$a = F/m$$
$$a = 100 \text{ newtons}/10 \text{ kg}$$
$$a = 10 \text{ m/s}^2$$

The wagon accelerates at a rate of 10 m/s^2.

Newton's Third Law of Motion

"For every action, there is an equal and opposite reaction."

Newton's third law of motion states that for every action, or force, there is an equal action in the opposite direction. Think of kicking a ball. As your moving foot causes force acting on the ball, the ball causes force acting on your foot, slowing your foot.

Newton's third law can be used to explain the critical aerospace concepts of lift and thrust, which are discussed in detail later in this chapter. Wings are designed to turn the air downward as it flows over and under the wing. Because the air is forced downward, the wing is forced upward, creating lift. Propellers, jet engines, and rocket engines create thrust by forcing air to the rear of the plane. As the air is forced toward the rear, the plane is forced forward.

Fluid Mechanics

Fluid mechanics is the study of fluids (liquid and gas) and the forces that act on them. Fluid mechanics is divided into fluid statistics and fluid dynamics. Fluid statics is the study of fluids at rest. Fluid dynamics is the study of fluids in motion. Fluid dynamics is of most importance to aerospace engineers because it is the basis for aerodynamics.

Aerodynamics is a subfield of fluid dynamics. ***Aerodynamics*** is the study of how air flows around solid objects. Airplanes, cars, and everything else that moves is affected by aerodynamics. Wind tunnels can be used to test the aerodynamics of models or entire craft. See **Figure 13-3**.

Laws of Conservation

The study of fluid dynamics and aerodynamics relies on the scientific understanding of conservation of mass, momentum, and energy.

Figure 13-3.
An object's aerodynamics, such as that of this parachute system, can be tested in a wind tunnel.

NASA Ames/Dominic Hart

Tools

Aerospace Engineering Tools

Aerospace engineers must be able to safely and effectively use a wide variety of tools and computer applications to successfully design, build, analyze, and troubleshoot components of aircraft, spacecraft, missiles, and high altitude vehicles.

Much of the field of aerospace engineering centers on aerodynamics, which is the study of air and how it reacts to an object moving through it. Wind tunnels are used extensively to test how moving air affects different designs. See **Figure A**. After a wing is designed, it can be placed inside a wind tunnel. Air is passed over the wing at given speeds. In this manner, the wing can be tested to see how much lift, drag, and turbulence it creates. Wind tunnels are used to test most anything that will pass through the air or have air pass over it.

Figure A.

NASA

Meters and gauges are used to measure flow, temperature, pressure, viscosity and much more in the study of fluids. An aerospace engineer might use these meters to study how a given material might react to increasing temperatures as a result of pressure increases.

Advanced software packages are used for mathematical computations, analysis, and visualization. Because accidents in this field are so catastrophic, extensive simulation and testing must be done to ensure that everything is reliable before physical testing can take place.

The law of conservation of mass states that mass cannot be created or destroyed. Although it can be rearranged or changed, it is never created or destroyed. Mass (m) can be found by dividing density (ρ) by volume (v).

$$m = \rho / v$$

You can calculate the mass of any material if you know the density and volume. Imagine you want to calculate the mass of a cup of water. You know that one cup of water is equal to 250 mL. At 40°C, the density of water is 0.9922.

$$m = 0.9922 / 250$$
$$m = 0.0039688$$

The law of conservation of momentum states that momentum remains constant until acted on by a force. Momentum (p) is the mass of an object (m) multiplied by its velocity (v).

$$p = m \times v$$

Imagine you want to calculate the momentum of a 2,000 kg truck moving at 20 m/s south.

$$p = 2{,}000 \text{ kg} \times 20 \text{ m/s south}$$
$$p = 40{,}000 \text{ kg} \times \text{m/s south}$$

The law of conservation of energy states that energy remains constant and is not created or destroyed. Energy can be converted from one form to another, but it cannot be created or destroyed.

Principles of Flight

Aerospace engineers must understand the principles of flight and the scientific concepts behind these principles in order to understand and design aircraft. Fixed-wing aircraft, which include airplanes and gliders, are heavier than air and create lift using their wings. There are four forces that act on fixed-wing aircraft: lift, thrust, drag, and gravity. **Figure 13-4** shows the forces that act on aircraft.

Lift

The principle of lift is essential for flight. The wing of a plane creates a downward force on the air, which in turn creates an upward force on the wing. This is called ***lift***. The shape of a plane's wings contributes to its lift. The shape of a wing is called an airfoil.

Bernoulli theory and Newtonian theory are two popular theories of how lift is created, but neither one is entirely true. Both theories were created to describe phenomena and were later applied to describe lift.

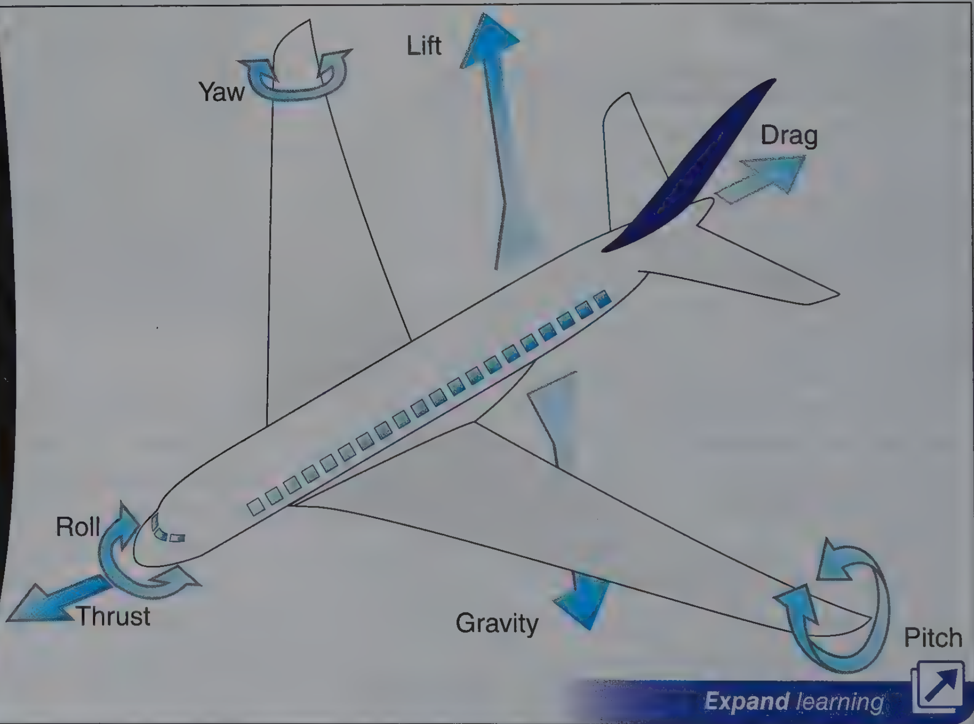

Figure 13-4.
The four forces of lift, drag, thrust, and gravity act on aircraft.

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Design

Flight Simulators

The word *simulation* is used to describe the imitation of something. Flight simulators imitate aspects of flight and are used to train pilots and design, test, and evaluate all aspects of flight in a safe and cost-effective way.

The most basic computer simulators involve desktop computers. Users interact with the computer to get a very general idea of such jobs as an air traffic controller or a pilot. The most advanced simulators include exact replicas of the cockpit of the craft a pilot is testing or learning to fly. High-definition screens show the pilots exactly what they would see out their windows if they were flying. The simulators are mounted on hydraulic jacks that move the entire cockpit to simulate what it would feel like to fly a particular craft.

Simulators can be used to test and evaluate the designs of aircraft parts and entire aircraft that have not yet been built. Software shows how the designs will perform. This saves time and money that would be required to build aircraft and helps remove the danger of flying completely untested aircraft.

As you know, engineers can go back to a previous step in the design process or even start over if their designs fail to meet their goals in testing. Simulation offers a much faster and less expensive evaluation process before design solutions are physically built.

Bernoulli theory of lift relies on the Bernoulli principle that an increase in fluid speed creates a decrease in pressure. See **Figure 13-5**. An airfoil is curved more on the top so that the air traveling over the wing has to travel farther than the air traveling under the wing. This causes the air flowing over the wing to flow faster relative to the wing than the air flowing under the wing, causing a low pressure zone above the wing and, therefore, lift. There is an area of lower pressure above most wing designs, but it does not completely explain lift.

Figure 13-5.

The air over this wing moves faster and creates low pressure.

NASA

Newtonian theory is based on Newton's third law of motion and the idea of a skipping stone. If you skip a stone across the water, the water pressure on the bottom of the stone keeps the stone on top of the water as long as there is sufficient velocity. Newtonian theory is based on the idea that air particles hit the bottom of the airfoil and are deflected downward. This downward deflection of the air causes the wing to be lifted upward. **Figure 13-6** describes Newton's third law and its effect on lift. The flaw in this theory is that it assumes the top of the airfoil has no effect on lift. It has been proven that both the top and the bottom affect lift.

Regardless of the theory, it is known that the entire wing works together to create lift. Speed is an important consideration when calculating lift.

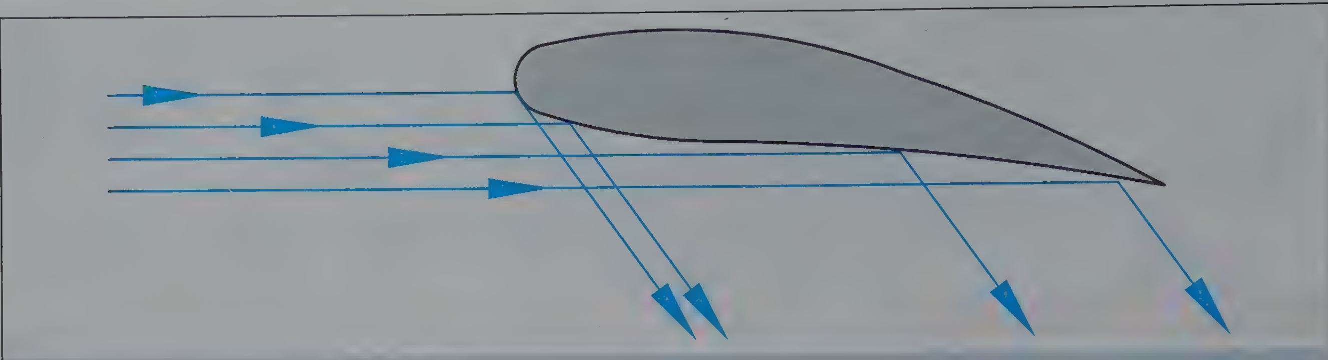

Figure 13-6.

One theory of lift is that the air bouncing off the bottom of a wing causes lift.

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Force (lift in this case) equals mass times acceleration (speed and direction). Therefore, increasing speed causes increased lift.

Lift is also affected by the density of the air, the velocity of the air moving over the wing, compressibility (springiness) of the air, viscosity (stickiness) of the air, shape of the wing, area of the wing, and the angle at which the wing approaches the air (angle of attack or inclination). Wing shape, inclination, and some flow conditions (viscosity and compressibility) are combined into one variable, which is designated as lift coefficient (*Cl*). While there is a formula for *Cl*, it is typically found using experimentation rather than calculation. Lift coefficient equals lift divided by the area of the wing times density times one-half the velocity squared.

$$Cl = L / (A \times \rho \times 0.5v^2)$$

The lift equation is as follows:

$$L = (Cl \times \rho \times v^2 \times A) / 2$$

Lift is also affected by the angle of incidence and angle of attack. The ***angle of incidence*** is the angle of the wing in relation to the airplane body. This angle is measured in relation to a line from the nose to the tail of the aircraft. This angle is fixed during construction and cannot be changed. The ***angle of attack*** is the angle of the chord line of the wing relative to the airflow. The chord line is a line drawn from the leading edge to the trailing edge of the wing. See **Figure 13-7**. As the front of the wing is lifted, the angle of attack becomes steeper and more lift is created. This is true as long as air is flowing smoothly around a wing with no turbulence or swirling. Smooth flow is called laminar flow. At a certain steeper angle,

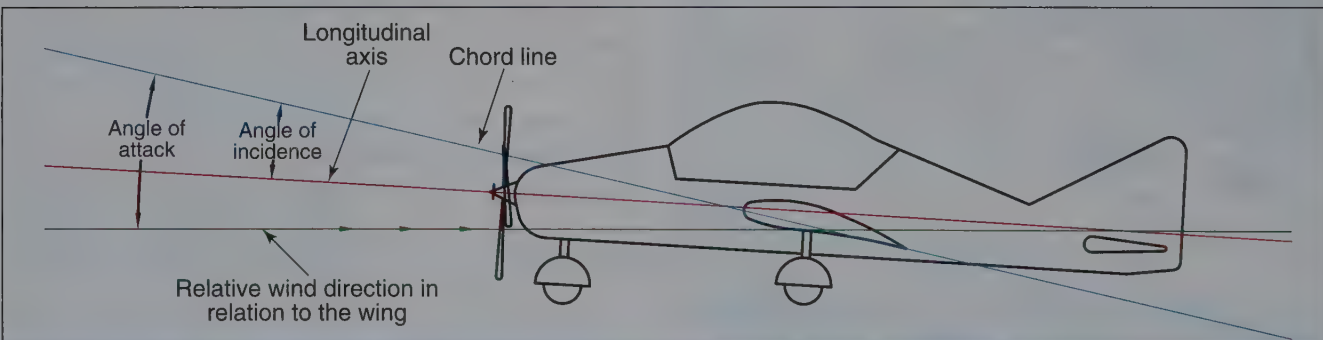

Figure 13-7.

The angle of incidence is the angle between the chord line of the wing and the longitudinal axis of the plane. The angle of attack is the angle between the chord line and the relative wind direction.

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airflow ceases to be smooth. The air swirls and mixes. This is called turbulent flow, and it creates a very dangerous condition known as stall, where lift is lost. See **Figure 13-8**.

Thrust

Thrust is the force that moves an aircraft through the air. In propeller planes or jet planes, gas (air) is being forced out the rear of the plane, causing the plane to move forward. Have you ever blown up a balloon and let go of it? The balloon flies around until it runs out of air pressure. The air coming out of the balloon creates thrust, which moves the balloon in the opposite direction. See **Figure 13-9**. This is the same concept as thrust in flight.

Newton's third law can also be used to describe thrust. The action is the forcing of air out the back of the engine. The equal and opposite reaction is the forward movement of the plane.

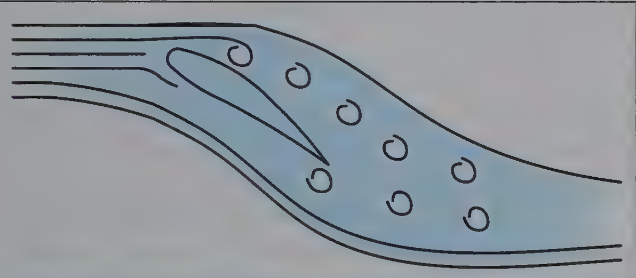

Figure 13-8.

If the angle of attack is too steep, the smooth laminar airflow changes to turbulent flow and lift is lost. This is a dangerous condition known as stall.

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Drag

Drag is an aerodynamic force that acts against the movement of an aircraft. As the plane moves through the air, drag is created in every part of the aircraft. It can be thought of in terms of friction. You have probably experienced that it is much more difficult to walk, run, or ride a bike into the wind. This is due to the force of the wind against you. This is the same force that acts on an aircraft in flight. The drag on an aircraft also changes as its speed and angle of attack change.

Calculating the drag of an aircraft depends on many variables. These include the velocity of the plane, the size and shape of the plane, the viscosity and compressibility of the air, and the angle at which the plane moves relative to the air. These variables are so complex that they are almost always determined experimentally.

Gravity

The weight is a force caused by the gravitational pull of the earth. The heavier the plane, the more gravitational pull it must overcome to stay in the air. Weight works in the opposite direction from lift. An increase in weight requires an increase in lift to stay at the same height. The opposite is also true. Think of a plane flying from London to Philadelphia. As the plane burns fuel, it gets lighter. As it gets lighter, it requires less lift to stay at the same elevation.

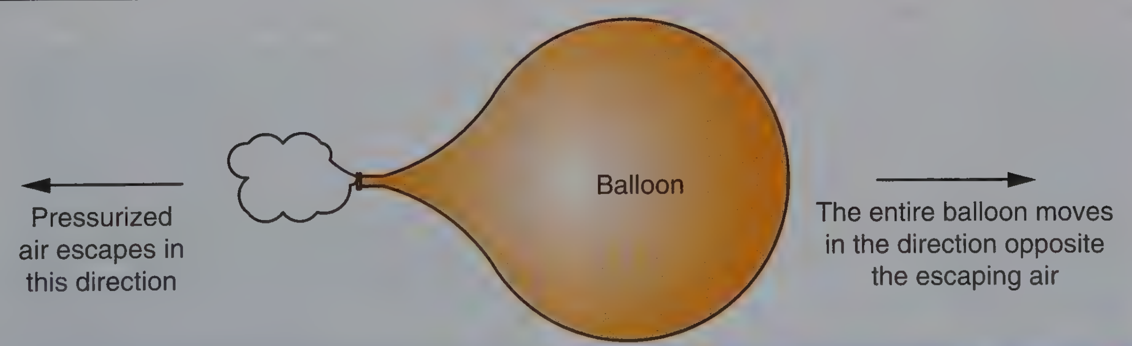

Figure 13-9.

Expand learning

The pressurized air escaping from the balloon creates thrust, causing the balloon to move in the direction opposite the escaping air.

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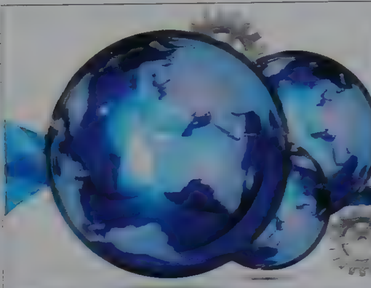

History

Aerospace Engineering in History

Orville and Wilbur Wright ran a bicycle sale and repair shop and a printing business. They used their businesses to fund their experiments in flight. In 1899, Wilbur Wright sent a letter to the Smithsonian requesting information about previous flight experiments. They collected all of the information they could from previous experiments and started working with gliders. After seeing other inventors killed in gliders, they decided it was imperative that they design gliders that could be controlled by the pilot before trying to add power. They watched birds very closely and saw that they arched their wings to create lift and moved their wings to change direction.

They did most of their building at their bicycle shop in Dayton, Ohio and their testing at Kitty Hawk, North Carolina. They chose Kitty Hawk because of its terrain, sand, and remote location. After building successful test gliders, they decided to build a full-sized biplane glider with a 17′ wingspan. This glider had a system to warp the wings for control and was the first manned glider flight.

In 1902, the Wright Brothers flew the largest glider that had ever been flown. This flight was not as successful because they were unable to create the necessary lift. Believing that their calculations were wrong, they decided to build a wind tunnel and begin testing wing designs. Based on their experiments and wind tunnel tests, they built a 22-foot glider with a rear stabilizer. The design was a breakthrough because it was the first that could be controlled, or steered, by the pilot through a series of wires. The wires were connected to the end of the wings. When the pilot pulled the wires, the ends of the wings warped, or twisted, relative to the rest of the wings to change the lift and drag characteristics like ailerons and flaps today. The flight was such a success that they decided to build a powered aircraft.

Figure A.

Brad Whitsitt/Shutterstock.com

In the winter of 1902 and 1903, the Wright Brothers and their mechanic developed a gasoline engine light enough and powerful enough to propel an aircraft. In December of 1903, they made the first sustained flights of a powered airplane.

By 1905, the Wright Brothers had an airplane that was fully controllable and could stay in the air for about a half hour or until they ran out of gas. See **Figure A**. In 1907, the US military bought their first plane from the Wright Brothers. Wilbur demonstrated flight in Europe and Orville flew in Virginia. Orders for planes began flowing in. They set up flight schools and manufacturing facilities around the country. Once everyone saw their planes, other people started building planes as well.

Wilbur died in 1912, and Orville sold the business and went back to being an inventor. Orville was on the original board of the National Advisory Committee for Aeronautics (NACA), which would eventually become NASA.

While weight is the easiest concept to grasp because we deal with the concept of weight every day, it is very different than the forces of lift and drag. Lift and drag are created by the physical contact between the aircraft and the air around it. Gravity is a field force, meaning that an object does not have to be in direct contact with another object in order to experience gravity.

The forces of lift, thrust, drag, and weight must be kept in proper balance for a plane to fly properly. Thrust and drag are forces that oppose each other. In order to move at a given speed, the aircraft must create enough thrust to overcome the drag created at that speed. To fly at a given height, the aircraft must balance the amount of lift created with the amount of gravitational pull.

Aerospace Engineering Applications

Aerospace engineers must be experts in all aspects of aircraft and spacecraft, or at least work in teams of engineers with various fields of expertise, so they can make informed design decisions. The success or failure of a project depends on these design decisions.

Aeronautics

Aeronautics deals with the flight of manned and unmanned craft inside the earth's atmosphere. Aircraft design can be broken down into four specific areas: aerodynamics, propulsion, stability and control, and materials and structures.

Aerodynamics

As described earlier, aerodynamics is the study of how air flows around solid objects. Aircraft are designed by engineers to be as aerodynamic as possible for their given function. For example, fighter jets are designed differently from large cargo planes. See **Figure 13-10**. Fighter jets are designed to be maneuverable at high speeds, while cargo planes are designed to haul large amounts of cargo in the most efficient way possible. Surfaces are designed to be smooth and create the least possible wind resistance. The more aerodynamic an airplane is, the more efficiently it will fly. This means the engines and fuel tanks can be smaller, the plane will be less costly to operate, and it will do less damage to the environment.

Propulsion

Engineers decide what engine type will best meet the propulsion needs of a given application. ***Propulsion systems*** create thrust for movement. Passenger airplane engines need to be quiet and efficient over great distances while fighter jets need tremendous thrust. Engineers are constantly working to make engines more efficient, quieter, and more environmentally friendly.

Propulsion or thrust can be provided in many ways, but all methods work on the principle of Newton's third law. In all propulsion systems, air is accelerated toward the rear of the plane, causing the plane to be propelled in the forward direction.

Propellers

Propellers create thrust. Propellers work like rotating wings that spin around a shaft. Propellers can have from two to six blades. A cross section of the propeller blade shows that it is shaped like a wing and, therefore, produces lift in the same way, but in a forward direction. Because the part of the blade closest to the center spins more slowly than the tip, the blade is twisted so the angle of attack is greater toward the center. This causes the thrust created by all parts of each blade to be equal. The air flowing into the propeller is accelerated toward the rear of the plane, causing the plane to move forward. **Figure 13-11** shows a common propeller blade.

Fighter Jet

Cargo Plane

Figure 13-10.

Fighter jets and cargo planes are designed differently because they have different purposes.

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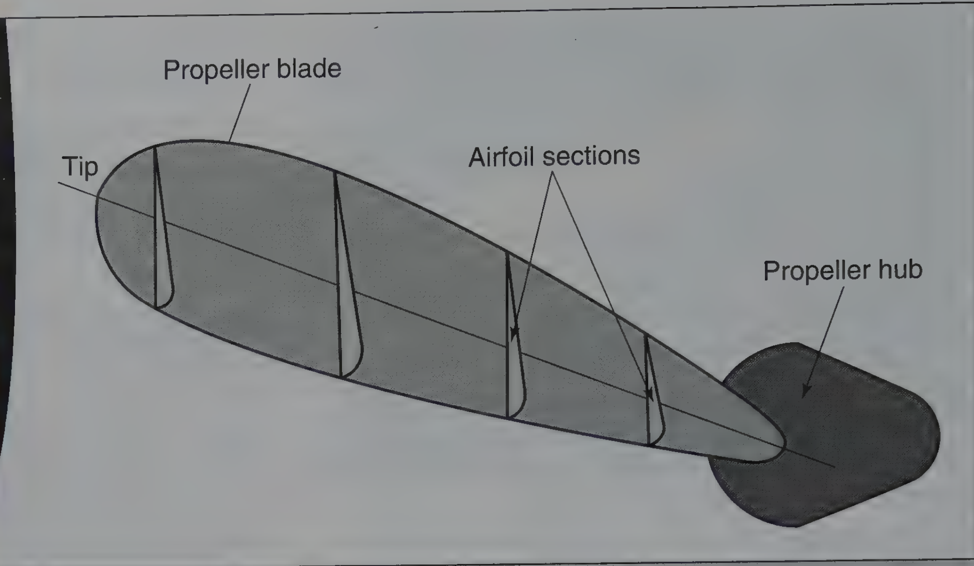

Figure 13-11.
The propeller blade is twisted so the angle of attack increases toward the center.

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Gas Turbine Engines

Gas turbine engines, also called jet engines, are the most common propulsion system in modern aircraft. While each kind of gas turbine engine works differently, they all share some basic principles. They all draw air into the front of the engine and compress the air with a fan. Fuel is injected into the compressed air and ignited. The pressure of the burning gas increases and escapes the rear of the engine through a nozzle. As the gas escapes, it is used to spin a fan. That fan is connected to the fan at the front of the engine. Therefore, the escaping gas is used to turn the compressor fan at the front.

Afterburning turbojet engines are used in fighter jets and supersonic (faster than the speed of sound) planes to provide additional thrust for short periods of time. There is a steep increase in drag at the speed of sound, which must be overcome in order to go faster than the speed of sound. Afterburning engines introduce additional fuel to the exhaust after it has gone through the turbine. This creates additional thrust but uses a great deal of fuel. **Figure 13-12** shows a turbojet engine.

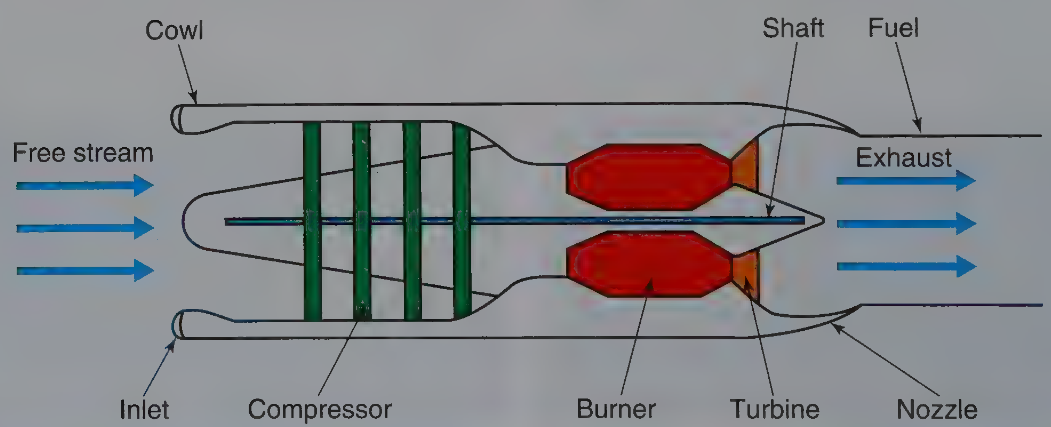

Figure 13-12.
Additional thrust is created in a jet engine when fuel is added to the exhaust.

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Rocket Engines

Rocket engines are used on extremely high-speed aircraft and spacecraft. See **Figure 13-13**. Inside rocket engines, fuel and oxygen are mixed and then explode in a combustion chamber. The exhaust is forced through a nozzle at an extremely high temperature and pressure. Rockets rely on Newton's third law of motion. As the exhaust is forced in one direction, the rocket is forced in the other. Rocket engines can use either solid or liquid propellants. With solid propellants, a heat source in the form of an igniter is used to start the reaction. Once the reaction is started, the engine burns until it runs out of fuel. Liquid systems are much easier to control because the sources of oxygen and fuel can be adjusted. While jet engines use the oxygen in the atmosphere, rocket engines carry their own oxygen. For this reason, rocket engines can operate in space where no atmospheric oxygen is available. Rocket engines are used to power high-speed aircraft like fighter jets and missiles because they provide the most power of any engine for their size and weight. Rocket engines also power spacecraft and rockets.

Rocket engine thrust depends largely on the design of the nozzle. Nozzles are designed on the principle that fluid flowing through a pipe speeds up as the diameter of the pipe decreases. For the same amount of fluid to flow through a smaller opening, it has to flow at a higher speed. Therefore, rocket nozzles are designed with a smaller diameter at the throat. The escaping gases are choked down through the throat of the nozzle and their speed increases.

Stability and Control

Stability and control include the ease of use of the controls as well as how an airplane reacts to the controls of the pilot. Planes must be easy to maneuver and easy for the pilot to control. Pilots must monitor tremendous amounts of information, such as navigation, altitude, fuel levels, weather conditions, and the location of other aircraft. Controls must be easy to find and to reach from where the pilot sits. Engineers design aircraft with these needs in mind.

Wings

The wings, which come in a wide variety of shapes, produce lift. The most basic type of wing is the conventional straight-wing design where the wings extend from the sides of the plane at right angles. The most common type of wing found on most commercial passenger aircraft is the swept wing. Swept wings extend from the

Figure 13-13.
The *Ares V*, used in NASA's *Constellation* program, used a rocket engine.

NASA

sides of the aircraft, but are angled toward the rear. Delta wings look like triangles from above. The front or leading edge can angle back as much as 60°. The tailing edge extends from the plane at about 90°. See **Figure 13-14**.

If you look closely at the wings on an aircraft, you will notice that they are usually not level. The outer ends of the wings are higher than the part of the wing that attaches to the aircraft. This upward angle is called the ***dihedral angle***, and it provides increased stability to the plane. See **Figure 13-15**. Dihedral angles can be seen in birds as they soar in the air. The outer tips of their wings are higher, providing stability to their bodies.

Control

The fuselage is the central body of the aircraft onto which the wings are attached. There are a number of hinged movable sections on aircraft that can be adjusted by the pilot to control the direction of flight. These are control surfaces, and they include flaps, ailerons, elevators, and the rudder. See **Figure 13-16**. ***Flaps*** are located on the trailing edge (rear) of the wing closest to the fuselage. Flaps are used at takeoff and landing to increase the amount of lift generated by the wings, especially at slow speeds. ***Ailerons***, which can cause the plane to roll along its horizontal axis for turning, are located on the outside rear of the wings.

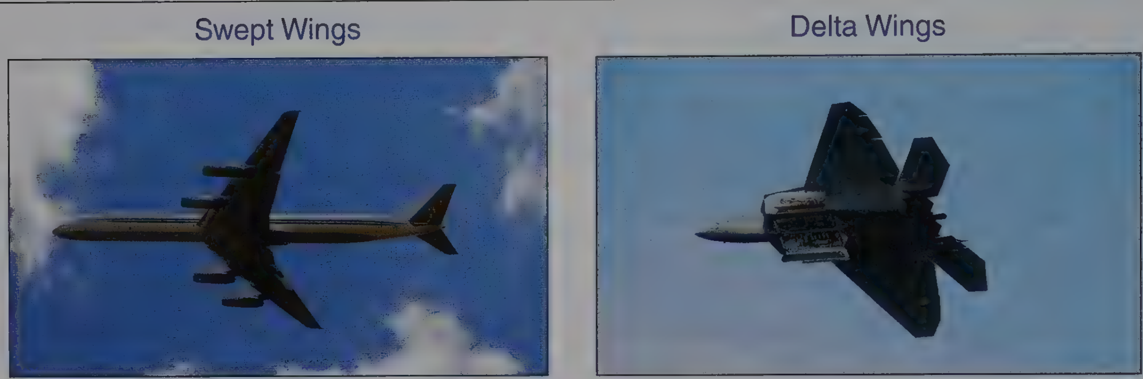

Figure 13-14.

Swept wings are angled toward the rear, while delta wings look more like triangles.

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Figure 13-15.

The dihedral angle of the wings on this plane provides increased stability when the plane is in flight.

Mikael Damkier/Shutterstock.com

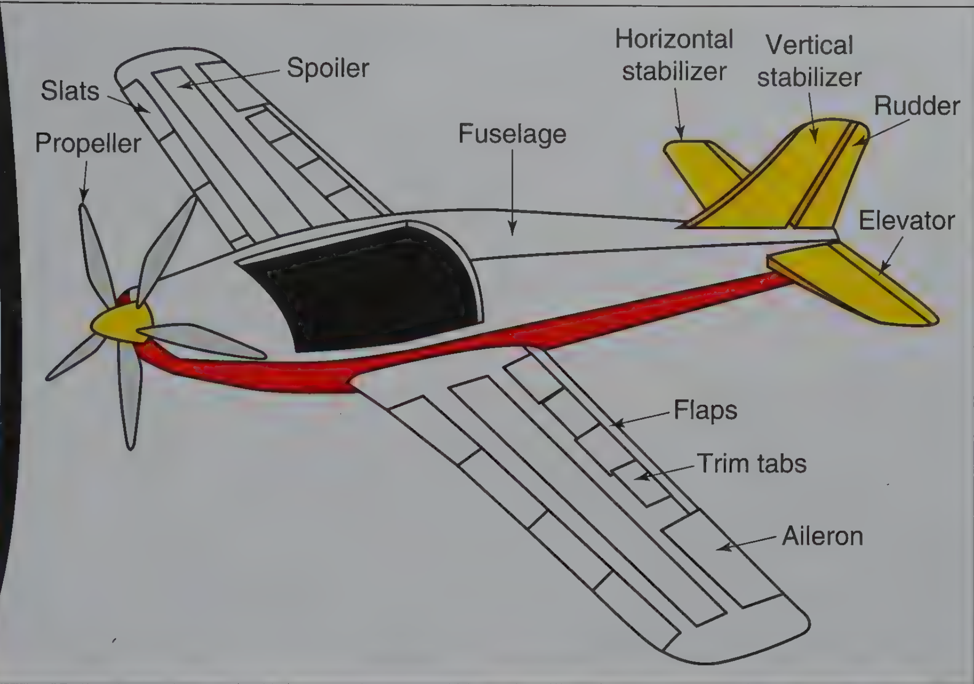

Figure 13-16.
The control surfaces of a plane can be adjusted to increase and reduce lift at different points in flight.

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If one wing produces more lift than the other, the wing producing more lift will raise and the other will lower, causing the plane to roll. Ailerons are important because they are used to make turns. Spoilers are located on the top surface of wings and can be raised to disrupt airflow, which increases drag and slows the plane. Some planes have slats on their front edge to change the amount of lift at takeoff and landing.

In the back of the plane, the vertical stabilizer keeps the nose of the plane from moving side to side. The horizontal stabilizer keeps the nose of the plane from moving up and down. The ***rudder*** is located on the back edge of the vertical stabilizer and is used to control ***yaw***, which is the side-to-side movement of the nose and tail. The ***elevators*** are on the back edge of the horizontal stabilizer and are used to control ***pitch***, which is the up-and-down movement of the nose and tail.

Structures and Materials

Engineers design airplanes to be strong, but also by as lightweight as possible. Lighter aircraft are more efficient, burn less fuel, cost less to operate, and create less pollution. Aluminum has long been the preferred material for making airplanes, but composites are becoming more popular. Composites are the combination for two different materials. When combined, they perform better than either of the two single materials. Think of a familiar product, such as fiberglass used in car bodies, boat hulls, and printed circuit boards. Fibers of glass are used to reinforce plastic and make it stronger so the finished product is better and more functional than either single material. Carbon fiber is a popular composite in the aerospace industry. Very thin fibers of carbon are woven together into sheets or mats and are then combined with a plastic resin. The result is a very strong but very light material. Composites are making planes lighter and, therefore, more fuel efficient.

Astronautics

Astronautics deals with the flight of manned and unmanned vehicles that travel outside the earth's atmosphere. Design considerations for travel into space are different and more complicated than for vehicles that travel within the earth's atmosphere.

Design of spacecraft must take into account the safety of any crew on board, the cost to operate, any cargo to be carried, and much more. Engineers search for the right combination of design, construction materials, propulsion systems, navigation, crew needs, and much more in the design of new space vehicles.

Travel into space has required tremendous amounts of design and engineering. In a relatively short period of time, we have sent vehicles and satellites into orbit, put astronauts on the moon, sent unmanned craft deep into space, and landed rovers on Mars. Each of these milestones required people to overcome unique design challenges relative to space. Each mission must overcome specific design problems to ensure successful missions and the safety of any crew involved. Space offers unique challenges. Therefore, it takes the best and brightest engineers in the world to solve these problems and to safely design and operate spacecraft to fly missions successfully and return safely.

Space offers many challenges and dangers to the crew. Engineers who design spacecraft and other equipment must make sure the crew is kept safe. The sun gives off dangerous radiation that is filtered out by the earth's atmosphere, but in space, the radiation is a real threat to people. Windows must be designed to filter out blinding ultraviolet (UV) rays. The outer skin of the spacecraft is made in two layers to protect against impact with particles and space debris at high speeds. Temperatures tend to rise on the spacecraft due to heat created by the crew and the electronics. Fluid is pumped through the cabin to absorb the heat. The heated fluid is then pumped through radiator panels outside the spacecraft so the heat is dissipated in space. The cooled fluid is then pumped through the cabin to cool it down.

Many of the engineering decisions that are made by aerospace engineers depend on the type of spacecraft they are designing. Several types include flyby spacecraft, orbiters, landers, rovers, and communications spacecraft.

Unmanned Spacecraft

Flyby spacecraft have been used to collect information about our solar system. They fly through the solar system collecting information and sending it back to the earth. They must be able to fly great distances and store data when they do not have line of sight with the earth. Line of sight is an imaginary line between earth and a spacecraft. If this straight line is not obstructed by something like a planet, there is said to be line of sight. That means the spacecraft can communicate with people back on earth. As planets and spacecraft move, there are periods of time when there is not a clear line of sight, and communication is lost. The *Voyager* spacecraft collected information about Neptune, Uranus, Saturn, and Jupiter.

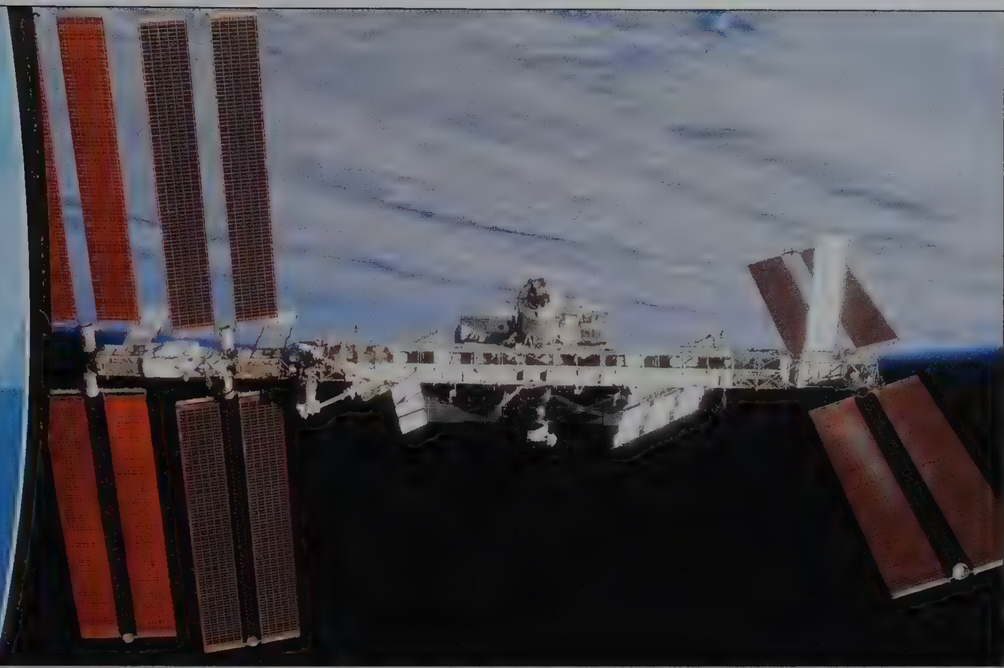
Orbiter spacecraft fly into orbit around a planet. They take pictures and record information, which they send back to earth. *Galileo* is an example of an orbiter. It was placed in Jupiter's orbit to monitor that planet. Orbiters must be designed to communicate and generate electricity even though they do not always have clear sight to the earth and the sun. The *International Space Station* is a manned satellite that orbits the earth at about 250 miles away. See **Figure 13-17**.

Landers are designed to land on other planets and send information back to earth. The Mars Pathfinder mission landed a rover on the surface of Mars. The lander used parachutes to slow its decent through the atmosphere.

Rovers are robotic vehicles delivered to a planet. They land on the surface and take pictures and soil samples. Their movement is controlled from earth. Information is sent back to earth. In the Mars Pathfinder mission, the rover sent back pictures, chemical data from rocks, and weather information. See **Figure 13-18**.

Communications spacecraft are placed in the earth's atmosphere and relay communication between the Earth and rovers and orbiters on other planets, relay communications between places on Earth, provide global positioning system (GPS) capabilities, and much more. See **Figure 13-19**. The most common communication spacecraft are satellites. ***Satellites*** orbit the earth in much the same way the earth orbits the sun. The centrifugal force created by their motion is in perfect balance with the earth's gravitational pull. Satellites move around the earth in orbits. The force of their movement pushes them away from earth. This is called centrifugal force. If it were not for gravity, satellites would fly off into space.

Figure 13-17.
The *International Space Station* is a manned satellite that orbits the earth.



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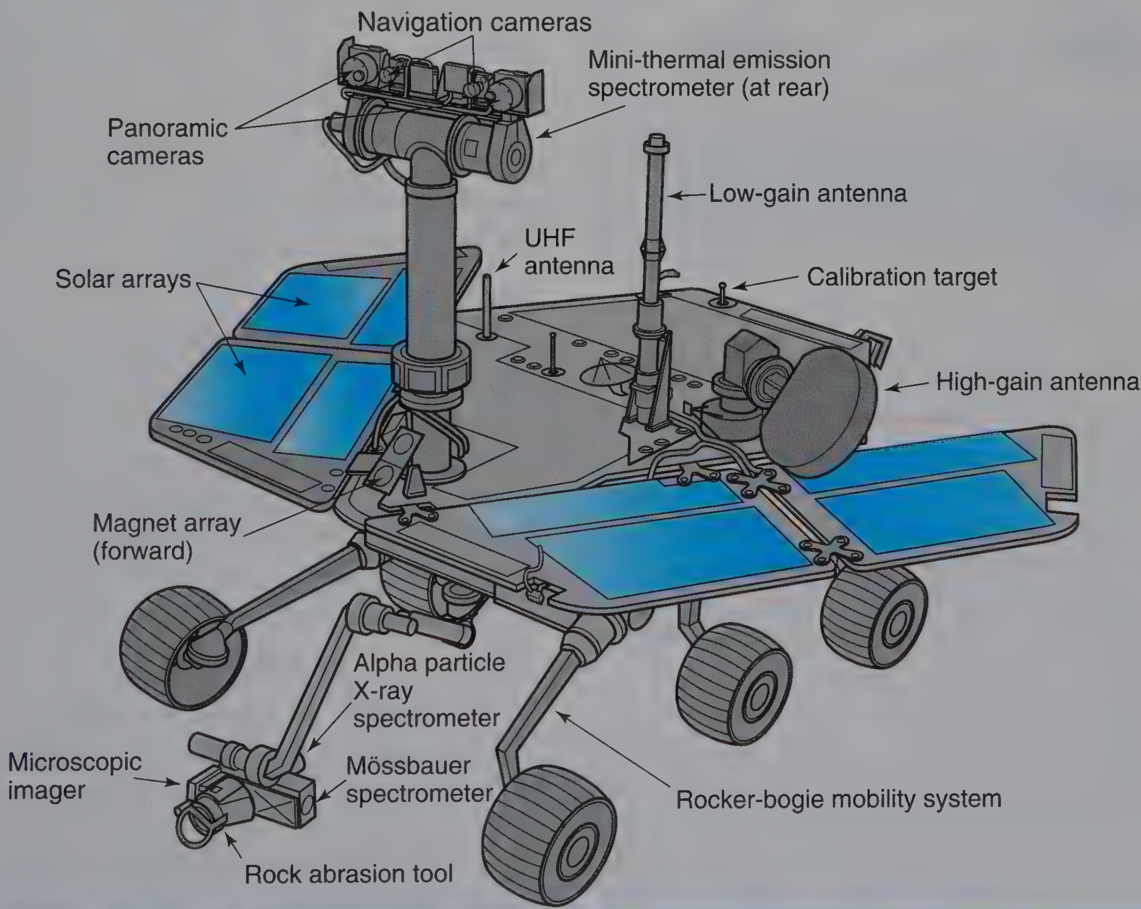

Figure 13-18.
This drawing shows the rover used in the Pathfinder mission.

NASA

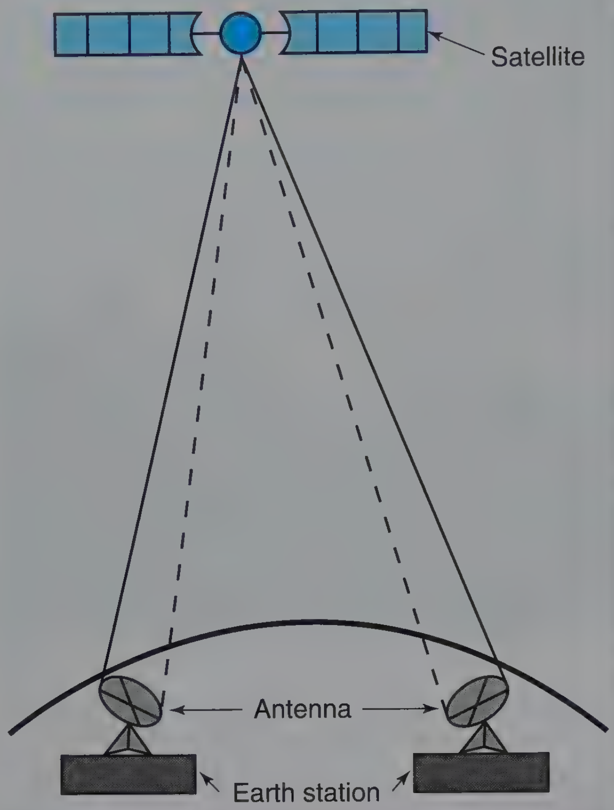

Figure 13-19.

Satellites are a type of communications spacecraft used to bounce signals around the world.

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Manned Spacecraft

Until recently, when you thought of manned space travel, you probably thought of NASA's space shuttles (orbiters), which have recently been retired. The five shuttles NASA built were launched over 130 times from 1981 to 2011. Spacecraft today are being designed, built, and operated not only by governments, but also by private companies.

Rockets

Manned spacecraft can be in the form of rockets or space planes. The word *rocket* can be used to describe a kind of engine or the whole vehicle that uses that engine. In terms of space flight, a rocket is a long, thin vehicle that launches from a vertical position with a rocket engine at the bottom, or rear, of the vehicle. Rockets have been used to send astronauts to the moon, lift satellites into orbit, conduct scientific research, restock and build space stations, and send probes into deep space. Manned rockets, like any other manned space vehicle, include a crew cabin that safely supports crew activities during flight. Since rocket engines require oxygen to burn, and there is no oxygen in space, spacecraft must carry their own oxygen.

Multistage rockets are built in sections. As each lower section runs out of fuel, an explosive charge breaks it off, and the next section provides propulsion. This way, the rocket keeps getting lighter as it climbs.

NASA is currently designing the Orion Multipurpose Crew Vehicle. See **Figure 13-20**. The Orion Multipurpose Crew Vehicle will be capable of housing up to four astronauts for deep space missions lasting up to three weeks. Orion includes a launch abort system to remove the astronauts if something goes wrong early in takeoff. The service module includes rocket engines for propulsion, oxygen for the astronauts to breathe, and solar panels to generate electricity in space. It has an adapter to connect it to the booster rocket and the guidance for the booster rocket.

Space Planes

Space planes fly like airplanes while in earth's atmosphere, and they fly like spacecraft while in space. The space shuttles were space lanes. Space planes have control surfaces like airplanes for moving within earth's atmosphere. These surfaces deflect air to change the position and direction. Main rear rockets provide thrust for lift and acceleration.

Spacecraft Control

For mobility in space, a variety of rockets are used because space is a vacuum, and control surfaces made to deflect moving air are useless. Main thrusters that are used for liftoff can be rotated. This is called gimbaling. As the direction of the escaping gas changes, the direction of flight changes. Rocket engines around their bodies control flight because space is a vacuum, and there is no air to deflect.

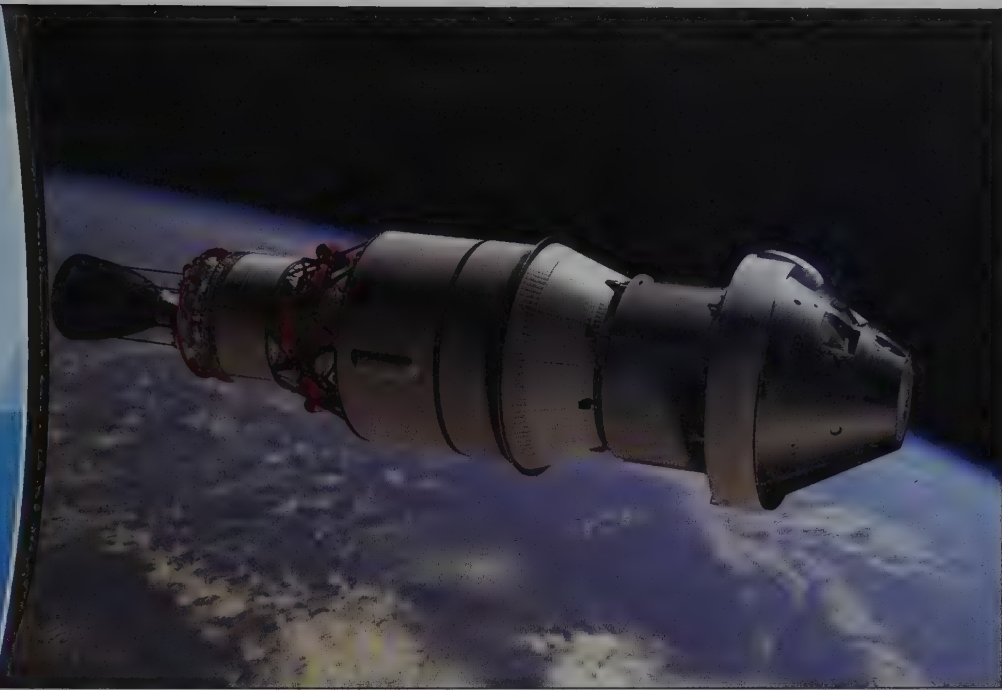


Figure 13-20.
Orion will be launched by the Space Launch System (SLS), which will have the highest lift capacity of any system ever built and will provide the opportunity to explore deep space.

NASA

Avionics

Avionics is a term used to describe aviation electronics. This is the combination of navigation, communications, flight control, monitoring, weather systems, and tactical electronics. Spacecraft avionics are designed with multiple backups in case primary systems fail.

Navigation in space is done by computer with sightings of stars. Sophisticated equipment on earth is also used to track the craft's position in space. Small rockets on spacecraft can be used to make slight corrections in course. Communications signals are sent back and forth between mission control on earth and the spacecraft. Equipment inside spacesuits provides for easy communication while the astronauts are outside working.

Basic Needs

Accommodations for basic needs must be made so the crew members can breathe, eat, sleep, and pass waste. Inside the cabin, a mixture of oxygen and nitrogen is circulated with fans so the environment is like that on earth. Special containers filled with lithium hydroxide absorb the carbon dioxide that the crew exhales into the air. Fuel cells that create electricity also create water for drinking. Dehumidifiers recapture water that is put in the air when the crew exhales. The food astronauts eat is much like frozen dinners because these meals can be nutritious and are easy to prepare. Astronauts use something like a toilet that evacuates waste in zero gravity using forced air. When they work outside, wastes are trapped inside their suits. Bathing can involve washing with wet towels or a shower where the water is vacuumed out. Trash can be expelled into space where it is burned in the atmosphere, or it can be brought back to earth. Astronauts may sleep in sleeping bags strapped to the wall, or they can sleep while floating with straps to keep them from bumping into things. See **Figure 13-21**.

Working in Space

Special design considerations must be made for extravehicular activities (EVAs) which are trips outside of the spacecraft. Astronauts wear special space suits that can keep them alive for up to eight hours. The suits are made of flexible airtight materials. Special equipment on their backs provides oxygen while removing carbon dioxide and water vapor. Visors provide protection from harmful UV rays. Astronauts leave their vehicle through a special room with two

Figure 13-21.
Because of the weightless environment, astronauts sleep in space either in sleeping bags or while strapped to the wall.

NASA

doors called an airlock. Once the astronauts are in the airlock, the outer door is opened into space. When they return, the door is closed, and a combination of oxygen and nitrogen is reintroduced into the room from tanks in the spacecraft. They can then open the other door into the spacecraft and the astronauts can go in and remove their space suits.

Astronauts can do almost anything in space that they can do on the earth's surface, but their tasks must be planned and designed properly. All aspects of EVAs are planned to consider that space suits are difficult to work in and will cause increased fatigue. When wearing space suits, astronauts have considerably less mobility because of the gloves they must wear; astronauts and their tools and equipment must be tethered so they cannot float away; and astronauts often have to work with only one hand so they can steady themselves with the other in a weightless environment. Tasks are specifically deigned to minimize small parts, loose parts, and tools because dexterity is limited. Parts are designed to be easy to use. Tether points are handholds that are designed into projects. All aspects of EVAs are designed to create the least possible amount of fatigue.

Reentry

In order to return to earth, spacecraft need to travel from space back into earth's atmosphere. This is called reentry. Objects enter the atmosphere at tremendous speeds due to gravity. Because of this speed, air cannot get out of the way of the craft fast enough and becomes compressed around the front of the craft. As pressure increases, so does temperature. Pressure combined with the friction of the moving air can create heat in the thousands of degrees Fahrenheit. Spacecraft use a variety of different heat shields to protect the craft and crew from this tremendous heat. Spacecraft use this friction as a means of slowing down on their way back to earth.

Commercial Space Travel

Until recently, only governments have been able to send people into space due to the finances and expertise required. Now, private companies are designing, building, and flying spacecraft into space.

This phenomenon started when the X PRIZE Foundation offered an incentivized competition. The X PRIZE Foundation offered to pay $10,000,000 to any nongovernment group that could send a manned spacecraft into orbit twice

within two weeks. The prize was won in 2004 by the space plane Space Ship One. The X PRIZE Foundation continues to offer prizes for private companies that meet specific goals in space travel and other areas of technology. This international effort has spurred development in private sector space travel around the globe. The idea of offering cash prizes for innovation is not new. Many prizes were offered in the early twentieth century for aircraft flight. This innovation helped to develop air travel as we know it today.

NASA is currently partnering with multiple private space travel companies in the development of new spacecraft. NASA is also contracting with private companies to resupply the *International Space Station*.

A whole new industry of manned and unmanned private space travel has been created, and the possibilities seem endless.

Aerospace Engineering in Action

You may wonder what specific types of problems aerospace engineers might be tasked with solving. Windmills have been used for hundreds of years to harness the power of the wind to pump water or grind grain. More recently, they have been used to generate electricity on a large scale. In response to global climate change and increased costs of fossil fuels, there has been increased investment in and government support for building wind farms. See **Figure 13-22**. Wind farms can create electricity on a large scale from wind, which is a renewable energy source that does not contribute to greenhouse gases. In very simple terms, a ***wind turbine*** works like a fan in reverse. Where a fan uses electricity to turn the blade and move air,

Figure 13-22.

Aerospace engineers design blades for wind turbines to make them as efficient as possible. Wind farms use the wind, which spins blades of wind turbines, to generate electricity.

TebNad/Shutterstock.com

a wind turbine rotates as the wind pushes it. This rotational energy is used to turn a generator, which generates electricity.

Aerospace engineers might be tasked with designing more efficient blades for wind turbines or designing blades specifically for areas where wind moves at slower rates. The concepts of aerodynamics and fluid dynamics that are used in flight are also used in the design of wind turbine blades. Blades produce the same effects of lift, yaw, angle of attack, and stall that are found in aircraft. In most turbines, blades can be rotated to maximize electrical output for given wind speeds and protect against overpowering or physical damage during times of extreme winds. A cross section of a turbine blade shows that its shape is like a wing. Along their lengths, turbine blades are twisted like propeller blades so that all parts of the blade effects the airflow evenly. Technology from aviation is increasingly being employed in the wind turbine industry.

Going Green

Global Climate Change

The single greatest threat to human civilization could be global climate change. The average temperature of the earth increased by about 1°F during the twentieth century. One degree may not sound like much, but average temperatures were only between 5° and 9° cooler than today during the last ice age. Increasing temperatures are likely over the next century and could cause increased droughts, sea level rise, tropical storm activity, and wildfires.

When you think of climate change and who might work to understand and control it, you might not first think of aerospace engineers. But aerospace engineers play a huge role in designing and creating the technologies that make the study of climate change possible.

NASA's *Eyes on the Earth* program uses more than a dozen satellites to monitor all aspects of global climate change, possible causes for climate change, and weather patterns. These satellites are used to monitor such details as ocean currents, sea-surface wind speed and direction, the sun's energy and radiation output, rainfall, ice and snow cover, sea ice, vegetation, particles and chemical components of the atmosphere, gases in the atmosphere, variations in the earth's gravity field, aerosols in the atmosphere, and clouds.

The information gained from these satellites is used to monitor the current conditions of our planet, study the way this data is related, explore causes of climate change, make future climate change predications, predict weather patterns, and look for ways to control climate change.

We have a long way to go before we fully understand climate change, but aerospace engineers have been and will continue to be at the forefront of technological breakthroughs that help us study our world. Maybe someday the aerospace field will find the keys to stopping and even reversing climate change.

Summary

- Aerospace engineers work in all aspects of aeronautics and astronautics.
- The largest professional society of aerospace engineering is the American Institute of Aeronautics and Astronautics (AIAA).
- Newton's three laws of motion have had a tremendous impact on aerospace engineering.
- Fluid mechanics is divided into fluid statistics and fluid dynamics. Aerodynamics is a subfield of fluid dynamics.
- The study of fluid dynamics and aerodynamics relies on the scientific understanding of conservation of mass, momentum, and energy.
- The four forces that act on fixed-wing aircraft are lift, thrust, drag, and gravity.
- Aerospace engineering is applied to aircraft and spacecraft.
- Aircraft design can be broken down into four specific areas: aerodynamics, propulsion, stability and control, and materials and structures.
- Spacecraft design is different from and more complicated than design for vehicles that travel within the earth's atmosphere. Considerations include the safety of any crew on board, the cost to operate, any payload to be carried, and more.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

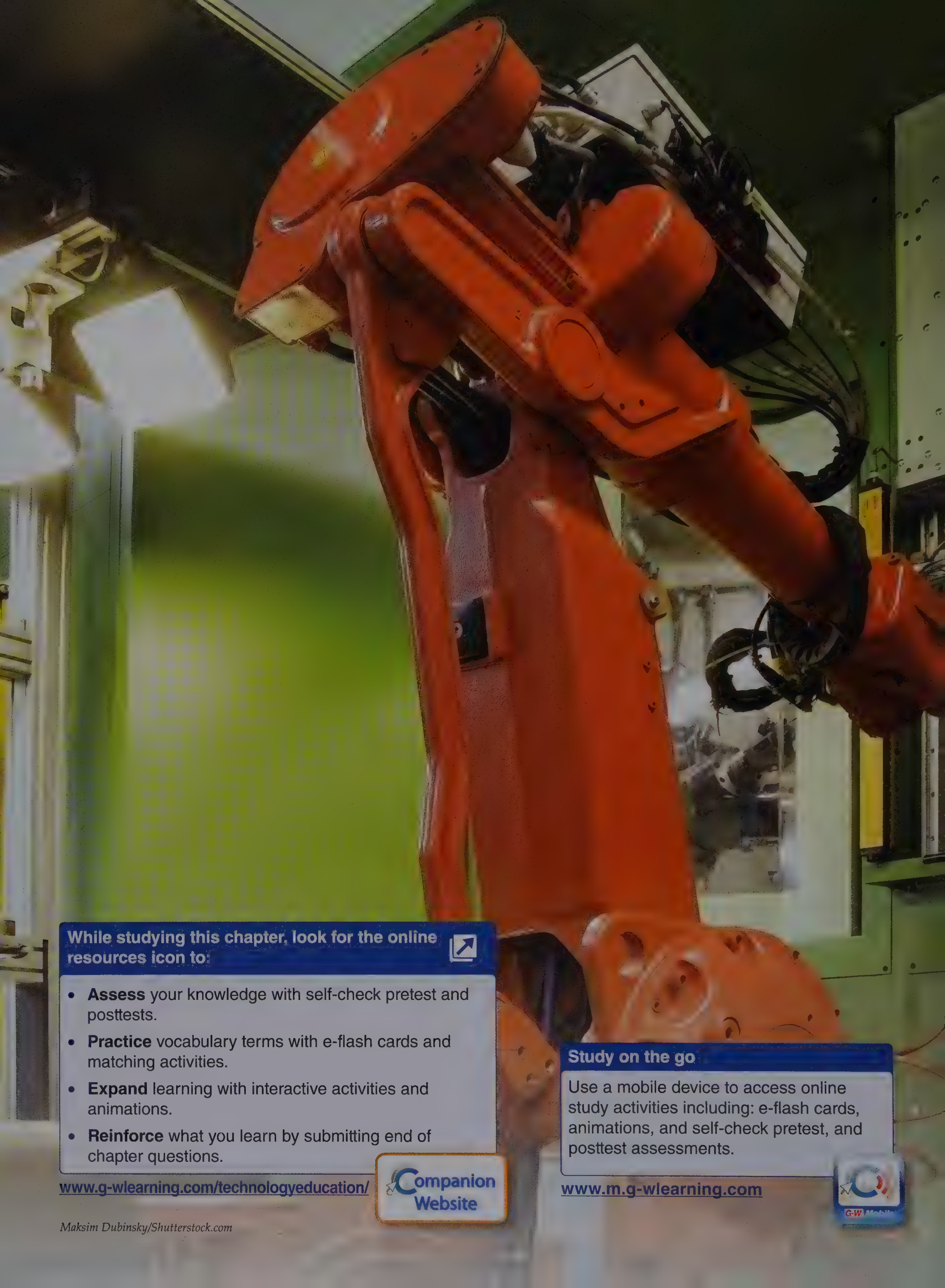
Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is *aerospace engineering*?
2. What level of education is required to become an aerospace engineer?
3. The law of inertia is also known as _____.
   A. the law of conservation of momentum
   B. Newton's first law
   C. Newton's second law
   D. Newton's third law
4. How can force be calculated for an object with constant mass?
5. What is Newton's third law of motion?
6. _____ is the study of fluids and the forces that act on them.
7. _____ is the study of how air flows around solid objects.
8. The mass of an object multiplied by its velocity is its _____.
9. The _____ theory of lift relies on the idea that an increase in fluid speed creates a decrease in pressure.
10. As air passes over a wing, the air is turned downward producing _____.
    A. drag
    B. thrust
    C. lift
    D. weight
11. The _____ is the angle of the wing in relation to the airplane body.
    A. angle of incidence
    B. chord line
    C. angle of attack
    D. stall
12. What is the most common propulsion system in modern aircraft?
13. The upward angle of a wing that provides increased stability to the plane is called the _____.
14. The *Voyager* spacecraft, which collected information from other planets, was a type of _____.
    A. flyby spacecraft
    B. orbiter
    C. rover
    D. communications spacecraft
15. How does a wind turbine work?

Reinforce learning



While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
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Chapter 14

Manufacturing Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *manufacturing engineering*.
- Explain how raw materials are harvested.
- Describe the manufacturing processes.
- Discuss applications of production management.
- List and describe the main areas of production control.

Key Terms

adhesion
alloy
casting and molding
ceramic
cohesion
combining
continuous manufacturing
cost control
custom manufacturing
drilling
environmentally conscious manufacturing (ECM)
facility engineering
fixture
flow process chart
forming
harvesting
intermittent manufacturing
jig
just-in-time (JIT) delivery system
manufacturing
manufacturing engineering
materials handling
metal
mining
operation process chart
operation sheet
plant layout
polymer
primary processing
process layout
product layout
quality control
raw materials
secondary processing
selecting and sequencing manufacturing operations
separating
Society for Manufacturing Engineers (SME)
thermoplastic
thermoset plastic

Practice vocabulary

We live largely in a manufactured world. Most of the things you encounter and use in your daily life have been manufactured. The bed you woke up in, the vehicle that brought you to school, the clothes you wear, and this book (or the device you are using to read this book) were all manufactured. Can you imagine a world without manufactured products?

Manufacturing is the process of changing raw materials to make them more useful. Think of a baseball bat. Trees are grown in the forest, and they have a certain value. The trees are harvested, and their value increases. They are cut into round poles a bit bigger than a baseball bat, and their value increases again. They are cut into the final shape of a bat and are sanded and coated with finish. They are then sold as finished baseball bats. At each step, a manufacturing process makes the wood more useful and more valuable. See **Figure 14-1**.

Manufacturing engineering is the design of machines, tools, and processes used to manufacture goods. Manufacturing engineers must have a broad understanding of tools, machines, engineering design, manufacturing processes, manufacturing systems, raw materials, computer systems, finances, people, and much more. They are often called on to use their extensive math, science, and technical backgrounds to solve complex manufacturing problems or design extensive manufacturing systems.

Manufacturing engineers often work in coordination with other engineers. For example, they might partner with product design engineers on the production of new products or with electrical engineers on the design of a new system. Manufacturing engineers also work with countless people outside the engineering field like people in marketing, sales, finance, labor, and management. See **Figure 14-2**.

Professional Aspects

The educational requirement for an entry-level manufacturing engineer is a bachelor's degree in manufacturing engineering or sometimes a related field like industrial engineering or mechanical engineering. For higher-level positions, master's degrees or doctorate degrees are usually required. To earn a degree in manufacturing engineering, courses must be taken in math, science, technology, and concepts of engineering.

Many colleges and universities offer two-year associate's degree programs in manufacturing engineering or manufacturing engineering technology. These degrees can lead into four-year programs or qualify graduates for jobs as technicians or in the manufacturing field. Manufacturing technicians often operate and maintain production equipment.

Figure 14-1.

Wooden bats are processed from the raw material of wood. The wood is processed into billets, and then the billets are refined into baseball bats.

Louisville Slugger Museum and Factory

Figure 14-2.

Manufacturing engineers work with other engineers, but they also work with people in marketing, sales, and management. They must be able to communicate well.

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In order to be accepted into an engineering program, students should earn the best possible grades in high school. Students should plan to take a minimum of one year of biology, one year of chemistry, one year of physics, and math through calculus.

The largest professional society for manufacturing engineers is the ***Society for Manufacturing Engineers (SME)***, with over 500,000 members in more than 70 countries. There are other societies that support specific areas of manufacturing engineering, such as the Society of Automotive Engineers (SAE), the Audio Engineering Society (AES), the Society of Women Engineers (SWE), the National Society of Professional Engineers, and the Institute of Industrial Engineers. See **Figure 14-3**.

Figure 14-3.

Many professional societies are open to manufacturing engineers, including the Society of Women Engineers (SWE).

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Manufacturing Engineering Principles

The principles of manufacturing engineering concern the materials used to manufacture products and the processes used to change these materials into useful products. Manufacturing engineers must be familiar with these principles because they are the foundation of manufacturing.

Manufacturing Materials

The materials used in manufacturing can be broken down into metals, ceramics, and polymers. When two or more of these materials are combined, they are called composites.

Metals are inorganic (do not come from living matter) materials with good conductivity to heat and electricity. Metals can be melted (are malleable),

meaning that they can be hammered into shape and are ductile, meaning they can be pulled into wire. Metals are typically found in rock. Examples of metals include iron, lead, copper, zinc, magnesium, calcium, and mercury. Two or more metals can be combined to form ***alloys***. See **Figure 14-4**.

Ceramics are very hard, inorganic, refractory (high resistance to heat), nonmetallic materials with little electrical conductivity. Ceramics include clays, porcelain, abrasives, glass, plaster, gypsum, and cement. Ceramics are used in dinnerware, plumbing fixtures, glass applications, abrasives like sandpaper, and heat resistant tiles like those used in fireplaces. They can also be used for knife blades and other cutting blades because they stay sharp much longer than metal blades. See **Figure 14-5**. They are used in joint replacement, bone replacement, and dental restorations.

Figure 14-5.

Ceramics are materials often used as knife blades because they stay sharp longer than metal blades.

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Polymers are organic (come from living matter) materials primarily made up of carbon and hydrogen atoms. They are noncrystalline, meaning that they do not have a crystal structure. Monomers are small molecules that can be bonded together in long chains to form polymers. Polymers can be either natural or synthetic. Natural polymers include wood, silk, rubber, DNA, and many other substances. Synthetic polymers are more commonly known as plastics. There are two types of plastics: thermoplastic, and thermoset. ***Thermoplastics*** like grocery bags can easily be reheated and reshaped with little or no damage to the plastic because there is little or no bonding between the chains, **Figure 14-6**.

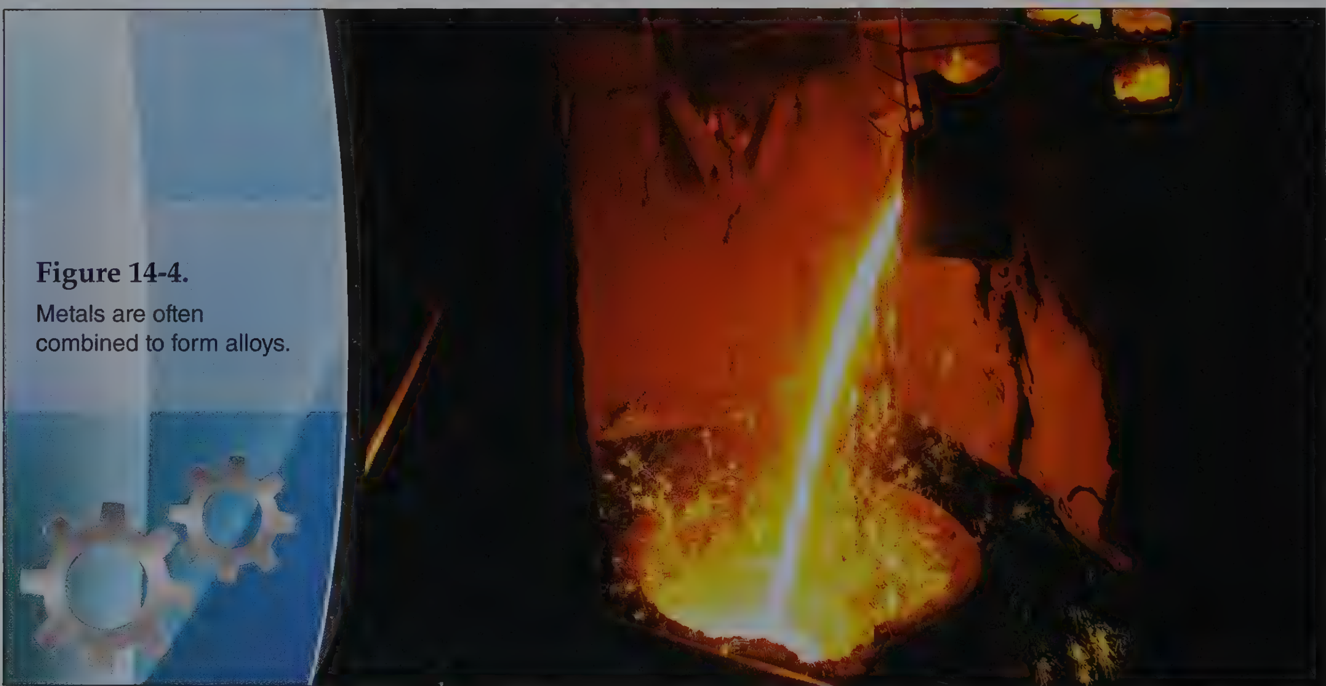

Figure 14-4.

Metals are often combined to form alloys.

Kekyalyaynen/Shutterstock.com

Figure 14-6.
Thermoplastics can be easily broken down and reshaped because of their organic makeup.

Huguette Roe/Shutterstock.com

Thermoset plastics are generally stronger than thermoplastics because they are cured with heat and pressure to crosslink the chains. Once they have been cured, they can no longer be reshaped and will remain rigid even when heat is applied. Plastic body parts for cars are made from thermoset plastics because they are much stronger.

Locating Raw Materials

The first step in the manufacturing process after a design has been approved is to obtain the necessary raw materials that will be used in the desired product. ***Raw materials*** are natural resources found in the earth, on the earth, and in the seas.

Raw materials are gathered by drilling, mining, and harvesting. Each technique has specific uses and applications.

Drilling is used to extract things like water, natural gas, oil, and other materials from under the earth's surface. Drilling is done by cutting a circular hole down into the earth until the desired depth is reached. A drill head is mounted on the end of a pipe. See **Figure 14-7**. The pipe and head are then turned, and the head drills the hole. The earth is drilled much the same way you might drill a hole in a piece of wood using a hand drill and drill bit.

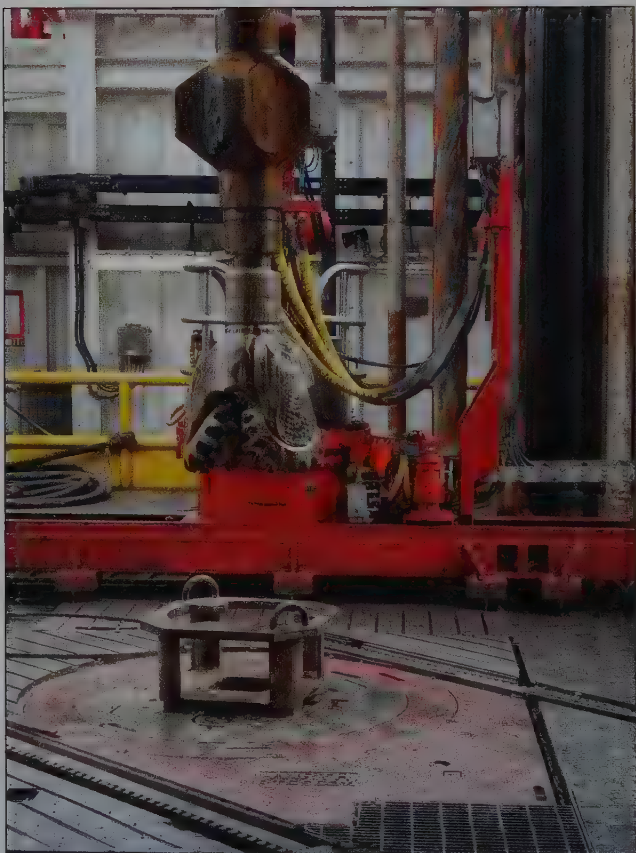

Figure 14-7.
Drill heads are mounted on a pipe. The head drills the hole as it turns.

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As the hole gets deeper, additional sections of pipe are attached and the hole is reinforced so it does not cave in. Mud is circulated down the pipe and out through the bit to float away debris. Drilling can be done on land or in the sea.

Directional drilling allows access to multiple reserves from one location. Horizontal drilling involves a vertical hole that then turns sideways and runs horizontally to access layers of resources. See **Figure 14-8**. Horizontal drilling has recently gained popularity in the natural gas industry. Huge deposits of natural gas have been trapped in very tight, dense shale rock formations. A process called hydraulic fracturing (hydrofracking) is being used to extract the natural gas from the shale. A horizontal hole is drilled through the shale formation. Blasts are sent out from the horizontal hole to create cracks in the shale. A mixture of water, sand, and chemicals is then pumped under great pressure from the horizontal hole into the shale. This process releases the natural gas from the shale so it can be extracted to the surface.

Mining is used to extract materials like metals, coal, uranium, iron, diamonds, and stone from beneath the surface of the earth. Mining is done in two ways. They are surface mining and subsurface mining. In surface mining, the soil and possibly bedrock are removed until the desired resources are exposed and can be removed. Subsurface mining involves digging tunnels or shafts to reach the desired resources. The soil and bedrock can be saved and used to fill in the mines after mining is complete. See **Figure 14-9**. Mine reclamation is the process of returning the mine as closely as possible to its former state.

Harvesting is the process of retrieving mature natural resources that grow on the earth. Cutting corn at the end of the season is an example of harvesting. In manufacturing, harvesting

Figure 14-8.
Horizontal drilling is used with a process called hydraulic fracturing, or hydrofracking, which extracts natural gas from shale.

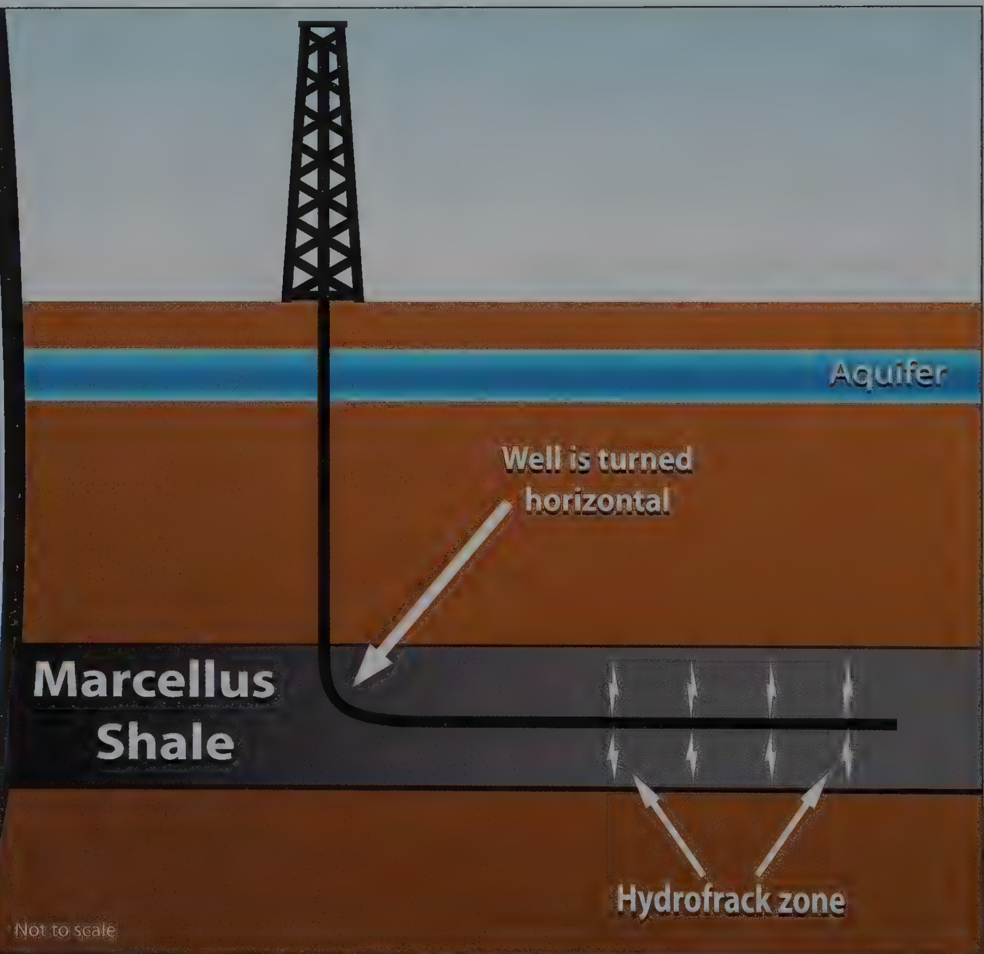

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Figure 14-9.

The extracted materials from mining can be used to restore the land to its previous state when mining is done.

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commonly refers to the cutting of trees for wood and wood products. Trees can be harvested using one of three main methods: clear-cutting, selective cutting, and seed tree cutting.

Clear-cutting involves harvesting all trees in a given area at the same time. After harvesting, the goal is to regenerate (regrow) a healthy forest that will serve as a wildlife habitat, stop erosion, and produce oxygen. Some forests are allowed to regrow naturally from shoots that come up from the stumps and roots of the trees that are cut down. Sometimes artificial regeneration is used where seeds and small trees are replanted to aid regeneration. This is particularly true in pine forests because they are less likely to regenerate naturally.

The process of harvesting single trees or small groups of trees as they reach maturity is called selective cutting. This process provides for a more natural forest with trees of all ages, but it does not provide the yield of clear-cutting.

Seed tree cutting leaves a certain amount of large trees per acre so the large trees will drop seeds and aid natural regeneration. See **Figure 14-10**.

Figure 14-10.

The three types of harvesting trees are clear-cutting, selective cutting, and seed tree cutting. Each type has a different impact on the forest.

Goodheart-Willcox Publisher

Whether natural resources are drilled, mined, or harvested, environmental regulations dictate that every effort be made to protect the environment and the areas be returned as close as possible to their natural condition when the gathering of natural resources is complete. Regulations are set forth and enforced by the US Environmental Protection Agency, the US Department of Interior Office of Surface Mining, and other agencies at the federal level, as well as state and local agencies.

Manufacturing Engineering Processes

Many specific processes are used to shape raw materials into standard stock and to shape standard stock into finished products. Manufacturing engineers do not typically operate machines and process materials themselves, but they must be familiar with these processes so they can design the systems of manufacturing and manage the

Going Green

Environmentally Conscious Manufacturing

The manufacturing sector consumes a tremendous amount of energy and produces vast amounts of waste to make products. While green manufacturing can be more expensive in some ways, it can cut costs in many others. Manufacturers all over the world are trying to cut their energy use, reduce the amount of waste they produce, use natural and biodegradable solvents and cleaners instead of petroleum-based solvents, and reduce their carbon footprints. Carbon footprint describes the total amount of greenhouse gases, such as carbon dioxide and methane, that are emitted into the air as a result of the company's processes. Carbon footprint can be decreased by using less energy and materials, using renewable resources where possible, and purchasing supplies from companies that do the same.

Environmentally conscious manufacturing (ECM) is a process concerned with the entire life of a product from the time the raw materials are gathered to the time the product's life is over and it is disposed. ECM tries to minimize scrap, to reduce or eliminate hazardous waste, and to make the most effective use of natural resources. See **Figure A**.

Consumers are becoming more interested in all-natural products and organic products. They want to know they are supporting businesses that put the environment first by not polluting. Now more than ever, consumers are willing to pay a premium for this peace of mind. Companies are now using their environmental standing as a marketing tool to consumers.

Figure A

max blain/Shutterstock.com

Saving on energy costs can directly affect the bottom line. As energy costs continue to increase, the buyback period (the amount of time it takes for savings to equal upfront costs) of energy-efficient equipment, lighting systems, and climate control systems continues to decrease. Simple behavioral changes can also affect energy consumption. Training programs to teach employees the benefits of turning off lights when a room is empty, shutting down and unplugging computers and other electronic equipment, and general awareness of energy management are increasingly popular.

Waste is being reduced by making use of more recycled materials and designing processes to ensure minimum possible waste is generated. When recycled materials are used, no new resources are consumed. Efficient design of manufacturing processes significantly decrease the amount of waste created. Manufacturers are finding creative ways to reuse their waste in their operations or sell/give it to others who can make use of it.

Environmental regulations with regard to pollution are getting stricter and manufacturers are forced to comply with new regulations. Manufacturing engineers are on the forefront of trying to make design production techniques more efficient with less impact on the environment.

people who do this job. Manufacturing engineers are responsible for determining the processes that will be used, the specific equipment and techniques used in each process, and the order in which the steps will be completed.

Primary Processing

Once materials have been gathered, they must be processed into standard stock. Standard stock describes the size, shape, and characteristics of materials commonly available to consumers. For example, trees are cut into standard size lumber to make furniture and build houses. Metal products are commonly processed into ingots (blocks), bars, rods, and sheets. See **Figure 14-11**. After oil is drilled, it is refined into products like gasoline, kerosene, diesel fuel, heating oil, solvents, asphalt, and petrochemicals (used in the production of plastics). This is called ***primary processing***.

Secondary Processing

Standard stock materials are made into useful products through ***secondary processing***. Common secondary processing techniques are separating, casting and molding, forming, and combining. For example, starting with a stack of sawn lumber and making furniture is a secondary process.

Separating

Separating is the process of cutting materials to the desired size or shape. This can be done through mechanical, heat, or chemical separating. You are probably most familiar with mechanical separating. Mechanical separating involves cutting or chipping materials apart. Scissors, shears, saws, and drills are common mechanical separating tools. Scissors and shears cut by shearing while saws and drills cut by making chips. Metals and plastics are often cut by heat separating. The material is heated along a line until it melts away. Cutting torches are used to separate metals like steel and iron. See **Figure 14-12**.

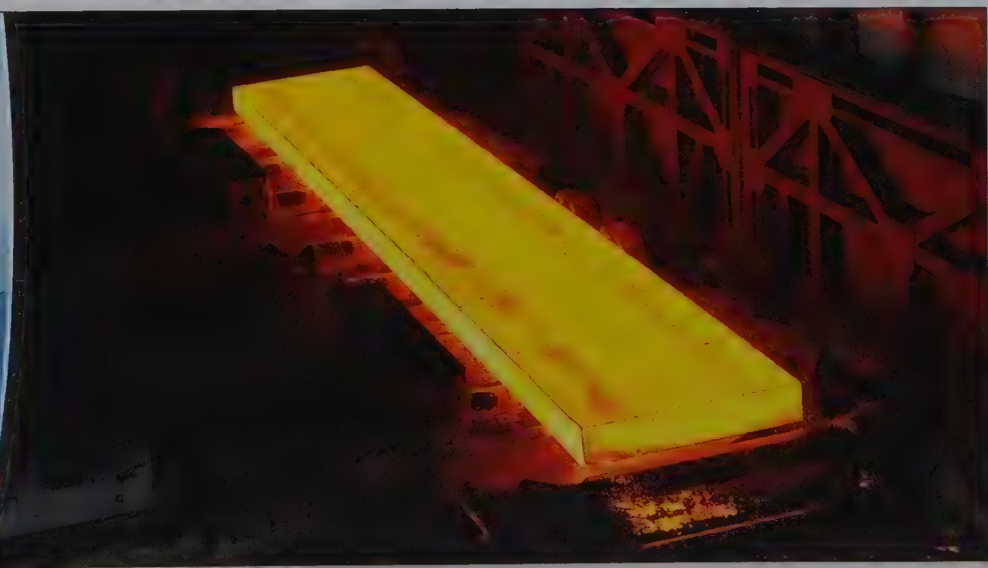
Figure 14-12.

For metals, the process of separating involves cutting torches.

Bogdan VASILESCU/Shutterstock.com

Figure 14-11.

An example of primary processing is metal that is processed into a standard-size bar.



jordache/Shutterstock.com

Chemical separating uses an acidic material to etch away unwanted materials. Unwanted copper is often etched away to create the desired circuit paths on circuit boards for electronics.

Casting and Molding

The ***casting and molding*** process involves changing materials to a liquid or plastic state (soft enough to be reshaped) and then shaping them in or around a mold. In casting, the material is changed to a liquid state by adding water or other chemicals or through heating. The liquid is then poured into a mold and allowed to solidify in the desired shape, **Figure 14-13**. In molding, the material is softened to a plastic state by heating or by adding water or other chemicals and then forcing the material into or around a mold.

Forming

Forming is a mechanical process used to change the shape of materials through compression, bending, or stretching. Materials are heated and compressed or hammered into a desired shape through forging. Forging is a forming technique where heat is applied to soften the material. The material is then pressed flat, squeezed together, or forced into a desired shape through pressure. Some products are forged by hand, while mass-produced products are forged using industrial machines. See **Figure 14-14**. A horseshoe is an example of a product that is forged.

Figure 14-13.

When casting, materials are changed to a liquid or plastic state, then cooled back to a solid state inside a mold. This will cause the material to take the shape of the mold.

mehmetcan/Shutterstock.com

Figure 14-14.

One type of forming is forging, which can be done by hand. Horseshoes are forged by hand.

gudak/Shutterstock.com

The bending process is used to create products like school lockers. Metal is bent until it reaches the desired shape. The stretching process can be used to create thin wire from a standard stock of a much larger diameter. The stock is drawn, or pulled, through hollow dies (molds) that have holes slightly smaller than the stock. To make large changes in diameter, multiple dies are used in a line.

Combining

The vast majority of manufactured products consist of multiple parts that have been joined together, or combined. The ***combining*** process joins parts through mechanical assembly and bonding. Mechanical assembly involves the use of mechanical fasteners like screws, bolts, and rivets. Some parts are made so they can be pressed together under great force. Sheet metal parts are often bent to fit together. Bonding is done in two main ways, adhesion and cohesion. ***Adhesion*** is the bonding of two materials using an adhesive material like glue or cement. In ***cohesion***, heat or pressure is used to join two materials. The most common cohesion technique is welding.

Manufacturing Engineering Applications

Manufacturing engineers are charged with designing and controlling the manufacturing process. They decide what type of manufacturing will be most effective for the quantity of products to be manufactured. They design the system to be efficient and cost effective, while meeting the necessary quality specifications. Quality is discussed later in this chapter. Once the system is up and running, manufacturing engineers monitor all aspects of the process.

Production Management

Manufacturing engineers design all aspects of production from start to finish. They must fully understand all characteristics of the product(s) to be made and all specific requirements.

Manufacturing Types

The first step in the design and control of manufacturing is to determine what type of manufacturing will be used to manufacture the desired product. There are three manufacturing systems: continuous, intermittent, and custom. The system of manufacturing used is determined

History

Manufacturing Engineering in History

Henry Ford's first engineering job was with the Edison Illumination Company in 1891. During his time at Edison, Ford designed and built two small self-propelled vehicles using internal combustion engines. After leaving Edison, Ford started two automobile companies that failed. In 1908, the Ford Motor Company was incorporated with Henry Ford as vice president and chief engineer.

In the early 1900s, only the rich could afford to have automobiles. Henry Ford did not invent the automobile. He developed production techniques that made automobiles affordable for less wealthy people.

When the Model T was first produced, it was assembled using the common practices of the day. See **Figure A**. Workers and parts were brought to the car and they would build it in one place. This was a time-consuming process and required the workers to be experts in all aspects of the vehicle.

Henry Ford and the Ford Motor Company built a new assembly plant that was specifically designed for mass production on an assembly line. The plant opened in 1908. The cars moved through the plant and workers assembled parts as the cars passed. This process allowed workers to perform one task well all day long rather than having to be experts in the assembly of the entire car. The assembly line concept decreased production time from about 12.5 hours to about 93 minutes per car. The decreased production time made the cars much more affordable. By 1918, almost half of all cars in America were Model Ts.

By 1927, the entire process of making a car took place at the new factory in Dearborn, Michigan. See **Figure B**. Ford had a steel mill, glass factory, and the assembly line. The raw materials were brought in and all parts were made and assembled from start to finish on the property. The finished cars came out the other end.

Henry Ford is known as the father of the assembly line. The Ford Motor Company revolutionized the way products are made all over the world.

Figure A.

Courtesy of Ford Motor Company

Figure B.

Courtesy of Ford Motor Company

by the number of products to be produced and the facility in which they will be produced.

Continuous manufacturing produces the highest number of products at the highest quality and the lowest cost per part. Because setup costs are very high, continuous manufacturing is only used when the volume of parts to be made justifies the setup costs. Plants are designed to produce a specific part of a product. Machines are set for specific purposes and the setup is not changed. Lower-skilled workers are needed because they load and unload the same machine(s) all day. An assembly line making cars or car parts is an example of continuous manufacturing. At each station in the assembly line, the same exact process is completed over and over. For example, a worker might install the windshield in a car and does that same job on every car that passes by. See **Figure 14-15**. That worker becomes an expert at that one job and does it well all day.

Because of the repetitive nature of many manufacturing processes, robots can replace people. Robot arms are commonly used in manufacturing for loading and unloading parts, spraying paint and other finishes, welding, assembling, and more. They are capable of performing tasks that might be hazardous for people, such as working in high-temperature environments, lifting heavy objects, and spraying paints and other finishes in a paint booth. The use of industrial robots can decrease long-term costs, increase productivity, and improve quality.

Intermittent manufacturing produces smaller batches of the same part. The entire batch moves through the factory together. At each station, machines are set up for that one part. When that operation is complete, the parts move on to the next station. Machines are set up one time for that batch and then changed for the next batch. Workers must be more skilled so they can read the prints and set up the machines to perform the operations properly. The cost per part is higher in intermittent manufacturing because the workers must be more skilled and production time is lost each time a setup is changed for a new part.

Custom manufacturing is used to produce a single product or a small number of products, usually to meet a customer's particular need. See **Figure 14-16**. This requires highly skilled workers who can read the plans and set up machines to perform each task. Custom manufacturing is the most costly way to produce items. It is used to manufacture products like cruise ships, where not enough are produced each year to justify any other manufacturing system.

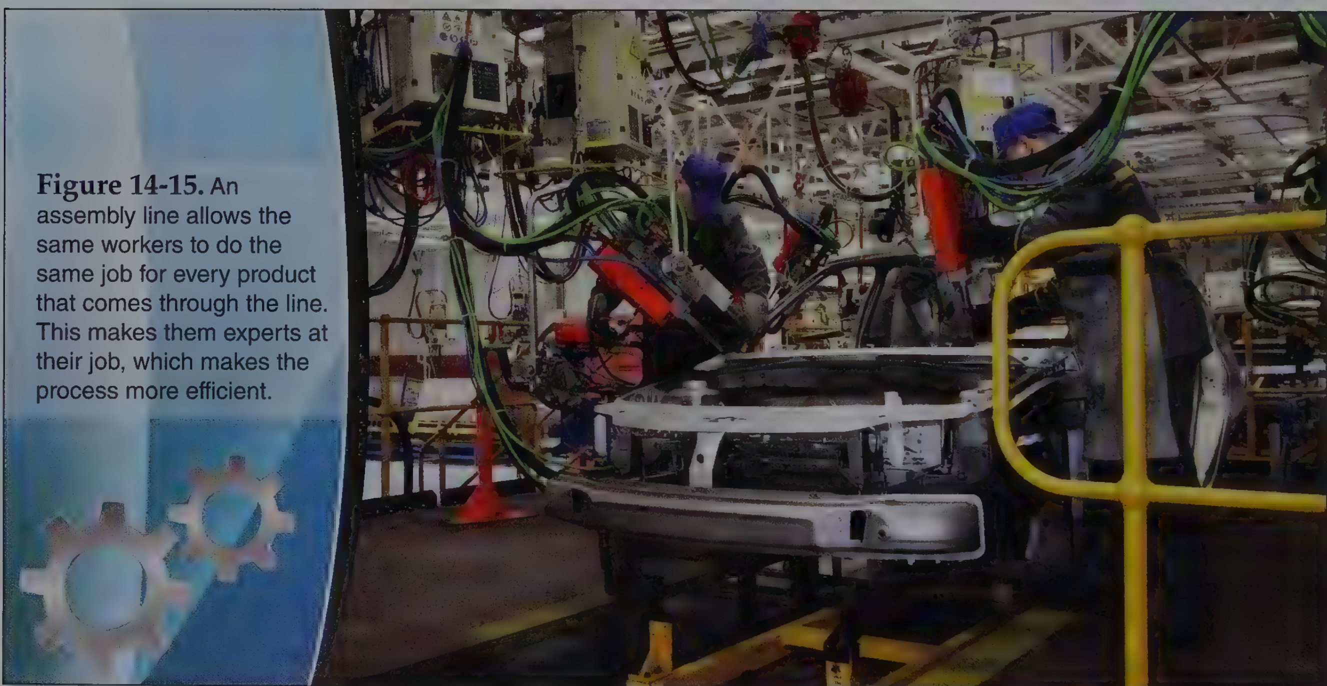


Figure 14-15. An assembly line allows the same workers to do the same job for every product that comes through the line. This makes them experts at their job, which makes the process more efficient.

Vasily Smirnov/Shutterstock.com

Figure 14-16.

For products that are only built one at a time, custom manufacturing is used. For example, ships are not produced in bulk, so a ship being built is an example of custom manufacturing.

Oleg - F/Shutterstock.com

Facility Engineering

Facility engineering is carried out by manufacturing engineers with expertise in tools, materials, processes, and the product(s) to be manufactured. Production facilities are designed specifically for the efficient production of the products that will be made in them. Whether the facility will be used for continuous, intermittent, or custom manufacturing, a lot of time and money can be saved if the facility is designed efficiently for the type of manufacturing it will be used for. Think of a factory designed to make cars. Manufacturing engineers design the facility for smooth, efficient flow of the cars down the assembly line. They design the flow of the parts to the cars at the right time and place. If a door fails to arrive at the right time, it could slow production on the entire line. Workstations for people and robots are designed to meet quality standards and be as efficient as possible.

Selecting and Sequencing Manufacturing Operations

Manufacturing engineers are responsible for deciding the ***selecting and sequencing manufacturing operations***. Manufacturing engineers decide what operations, or processes, will be used to create the product and in what order, or sequence, they will be performed. These manufacturing operations must be organized in the most efficient and economical way possible. The process and sequence will be laid out using a variety of forms.

Operation Sheet

The ***operation sheets*** are used to record and communicate the operation name, machines, and tooling outlined by the manufacturing engineer. See **Figure 14-17**. Operations are the processes used to change the shape of the materials in production. This includes cutting, sanding, bending, molding, and many more processes.

Operations Sheet					
Part Name: CD/DVD Holder End				Date:	
Part Number: 1			Material: Pine	Prepared By: MTB	
Operation Number	Operation Description	Machine	Tooling	Setup Time	Production Rate
1	Cut ends to length	Crosscut saw	Jig 1	10 min.	30 per hour
1	Sand faces	Palm sander	Sandpaper	1 min.	30 per hour
1	Sand edges	Palm sander	Sandpaper	1 min.	40 per hour

Figure 14-17.

The operations sheet describes the machines and tooling needed for a specific product or part of a product.

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Tools

Manufacturing Engineering Tools

Drafting and Design Capabilities

Manufacturing engineers often need to create, review, and modify drawings of parts, products, workstations, and facilities. Few still do this using manual drafting tools. Most now use computer-aided design (CAD) software. While manufacturing engineers are not drafters, they must often work on drawings or have other people do this work for them.

Computer Simulation

As in any other area, computer simulation can save a lot of time and money. Think of what it might take to set up a manufacturing operation and to see how it works. Computer simulation is much more efficient.

Jigs and Fixtures

Jigs and fixtures greatly increase the efficiency of repetitive operations. The terms jig and fixture are often used interchangeably, but they describe different things. Jigs are used to guide tools, and fixtures are used to hold parts while work is performed. A jig might be used to guide a drill bit to a desired location to drill a hole. A fixture might be used to hold a part in exactly the correct location on a milling machine while a groove is milled.

Jigs and fixtures speed production and decrease labor costs because there is no need to measure and lay out each operation. Once the machine is set up properly, part after part is loaded into the machine, work is performed, and the part is removed. Unskilled laborers can operate these machines because of the relatively simple repetitive nature of the work.

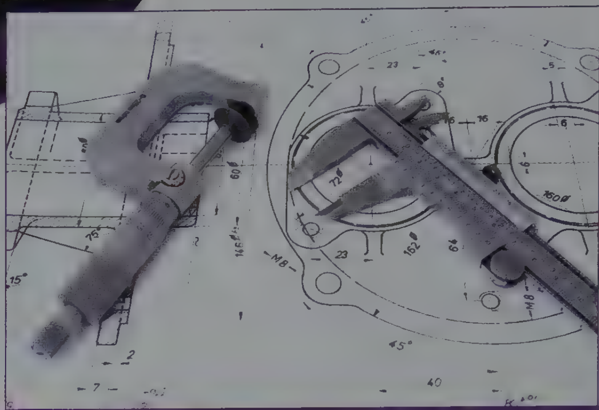

Figure A.

Adem Demir/Shutterstock.com

Stopwatches and Timers

Manufacturing engineers often study the efficiency of specific operations and try to save time wherever possible and to save labor and machine costs. The faster something can be made, the less it will cost to produce.

Measuring Tools

Measurement tools are a necessity in plant layout, process design, and quality control. Manufacturing engineers commonly use micrometers, calipers, and tape measures. See **Figure A**.

Production Charts and Schedules

Charts and schedules are used to design and keep records of things like material and product flow, plant layout, quality control, and scheduling.

Manufacturing engineers determine what processes will be necessary to change the standard stock into the final product. They determine what tools and machines will be used to perform these processes. They specify if any tooling is required. Tooling refers to jigs and fixtures, which are used to increase speed, accuracy, and safety of manufacturing processes. *Jigs* are used to guide tools to the correct location, and *fixtures* are used to guide a work piece. See **Figure 14-18**.

Flow Process Chart

Flow process charts are used to record and communicate the order of the processes dictated by the manufacturing engineer to make each part. See **Figure 14-19**. These charts typically outline the operation to be performed, the machine to be used, and any tooling required. Standard symbols are used to describe operations. Operations are marked with an *O*.

Jig

Fixture

Figure 14-18.

The piece of metal is being used as a jig because it guides the router in a straight line along the work piece. The table on the tile saw is a fixture because it guides the tile into the saw blade at the desired angle.

Christina Richards/Shutterstock.com; Johann Helgason/Shutterstock.com

Flow Process Chart

Product Name: CD/DVD Holder		Date:
Flow Begins: End O-1	Flow Ends: End T-2	Prepared By: MTB
Process Symbols and Quantities		Approved By: RAB

O Operations 3 D Delay ____ ▽ Storage ____

☐ Inspection 1 ⇨ Transportation 3

Part	Process	Process Symbols					Process Description	Tool	Tooling
1	O-1	O	⇨	☐	D	▽	Cut ends to length	Crosscut saw	Jig 1
1	T-1	O	⇨	☐	D	▽	Move to sanding station		
1	O-2	O	⇨	☐	D	▽	Sand faces	Palm sander	
1	O-3	O	⇨	☐	D	▽	Sand edges	Palm sander	
1	T-2	O	⇨	☐	D	▽	Move to inspection		
1	I-1	O	⇨	☐	D	▽	Inspect		Gauge 1
1	T-2	O	⇨	☐	D	▽	Move to assembly		

Figure 14-19.

The flow process chart is used to record the order of the processes to make each part or product.

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Transportation is marked with an arrow. Inspections are marked with a square. Delays are marked with a *D*. Storage is marked with a triangle pointing downward. Flow process charts are used to study the sequence of operations so products are made in the most efficient way. One chart is used for each individual part to be made, even if multiple parts will be made and assembled later.

Operations Process Chart

Operations process charts are used to study all operations in the manufacture of an entire product. See **Figure 14-20**. They show the processes involved in making each part as well as assembly operations. This way, manufacturing engineers can study the entire manufacturing process.

Plant Layout

Plant layout refers to the location of the materials that will be made into products and how they are moved through the plant, including such aspects as equipment layout, utility location, and traffic flow. Because plants produce a wide variety of products, plants are laid out in different ways. Manufacturing engineers must design their plant layouts to produce their products in the most efficient way. Resources need to flow easily through the plant from storage to the first machine and then through the manufacturing process. Storage must be provided for finished products until they are shipped. Traffic flows must allow for employee evacuation in the event of an emergency. Workers must be able to easily access rest facilities, break rooms, and offices. Most plants are designed using either process layouts or product layouts.

Process Layout

Process layout is commonly used in intermittent and custom manufacturing. Equipment is located based on the process it performs, **Figure 14-21**. For instance, think of a facility designed to build wooden cabinets. All of the rough cutting equipment might be located next to the lumber storage area to allow easy flow of rough lumber from storage to the planer, joiner, table saw, and radial arm saw. There might be a sanding area, a gluing area, and a finishing area.

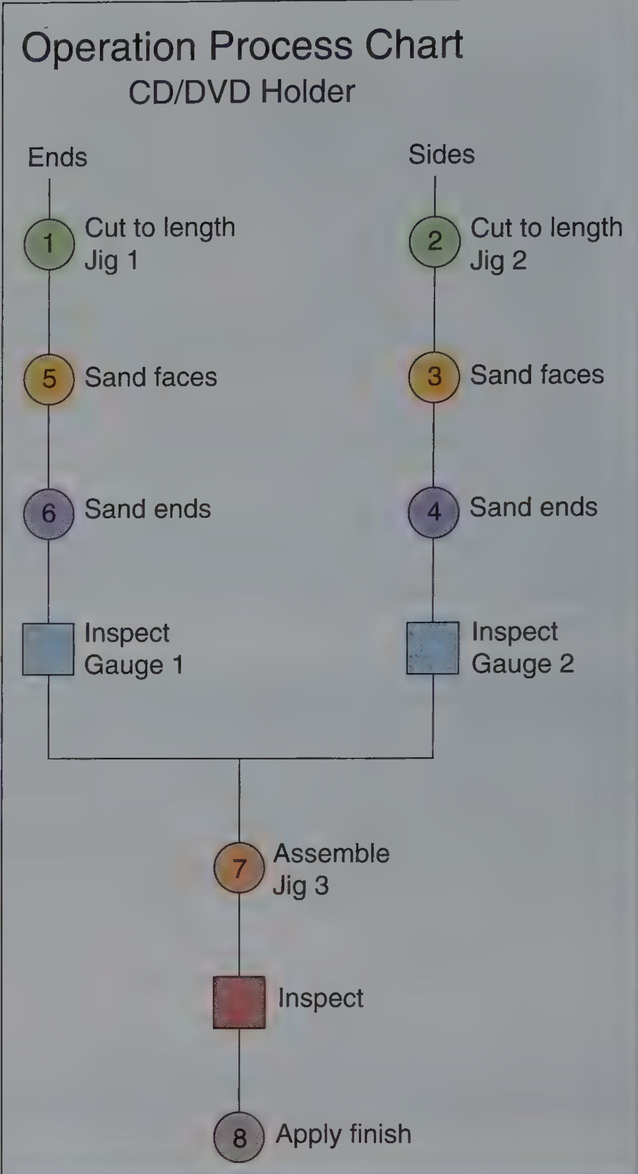

Figure 14-20.

The operations process chart shows the processes involved for an entire product, including the individual parts as well as the assembly operations.

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By grouping these like processes together, the plant is efficient for general cabinetmaking operations. As the specific product changes, the settings on the equipment might change, but the layout of the plant does not.

Product Layout

Product layout is commonly used for continuous manufacturing. The entire facility is designed around the manufacture of one product.

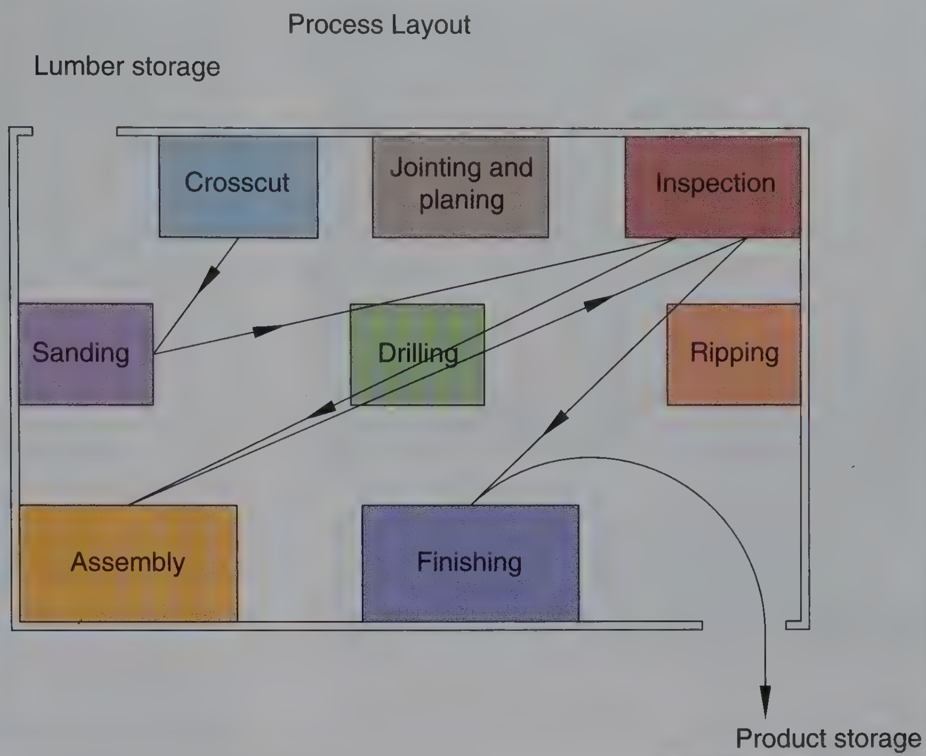

Figure 14-21. For a facility set up in process layout, the equipment is located according to the types of process, so that all similar equipment is together.

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Design

Design for Manufacturing

Though you may not think of it, manufacturing engineers can play a large role in product design. Customers can specify requirements for products like size, shape, material finish, tolerances, and more. Products are designed to meet those specifications.

Products are also designed for manufacture, meaning they are designed so they can be manufactured efficiently. Think of a plastic or metal product that will be made in a mold. It is much easier to mold parts with slightly rounded corners than sharp corners. Have you ever made a sand castle using a bucket? You fill the bucket with wet sand, turn it over, and lift the bucket away. How often are the top edges broken off? It would be easier to get a smooth result if the inside corner of your bucket was rounded. The same is true in manufacturing. It is not that sharp corners are impossible, but they are more difficult and, therefore, more expensive.

Manufacturing engineers might alter a design to reduce the amount of material required, include standard, inexpensive, readily available parts, decrease manufacturing or assembly steps, standardize parts, decrease the number of parts, or use less expensive materials.

Designing products specifically for ease of manufacturing can drastically reduce costs. This is one of many ways that manufacturing engineers can contribute to product design.

The machine that must be used first is located next to the material storage area. The next machine is located next to the first one and so on. The parts flow through the plant from one machine to the next with little or no wasted movement. See **Figure 14-22**. This is the most expensive way to lay out a plant because it must be changed when the product changes, but it is the most efficient and cost effective to operate. Cars and other vehicles are made in manufacturing plants that use product layout. Everything in the factory must be designed specifically for the vehicle being manufactured. The increased setup costs are made up in the savings in production costs over the thousands of vehicles.

Plant Layout Communications

Manufacturing engineers communicate their plant layout designs through drawings and sometimes 3-D models. The design must be communicated accurately so equipment can be placed properly and necessary utilities can be placed appropriately. Plant layout designs and models can be complicated with many operations happening at the same time and often on multiple levels in the plant.

Production Control

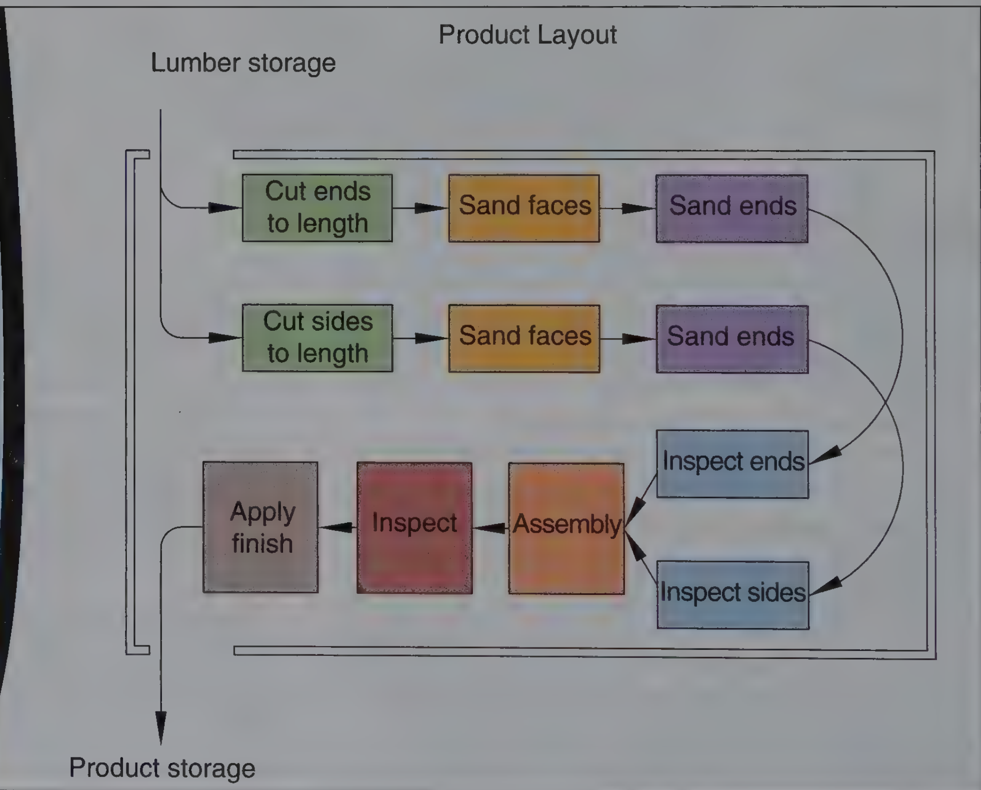
Systems must be put in place to ensure all products are produced to the desired quality specifications at the lowest possible price. This is the job of the manufacturing engineer. Manufacturing engineers design the manufacturing systems and then monitor every step of production for quality and efficiency.

Lean Manufacturing

Manufacturing engineers are always looking for ways to increase production and quality while cutting costs and ensuring worker safety. A popular philosophy called lean manufacturing focuses on the idea that all resources the company invests should directly translate to value the customer sees. Anything else should be eliminated to cut costs.

Lean manufacturing looks to eliminate seven sources of waste: overproduction, overprocessing, excess motion, excess inventory, defects, transportation, and waiting. Overproduction is the production of more parts in a batch than a customer needs, either because of error or because the customer's needs change after the order is placed.

Figure 14-22.
In a facility set up in product layout, the equipment is set up by sequence of operations for a particular product.



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Overprocessing occurs when more work is done on a part than the customer actually requires. Any unnecessary movements or motion of workers or equipment waste time, risk repetitive motion injury to workers, and increase wear and tear on equipment. Inventory must be kept to a minimum because raw materials, parts, or finished products that stay idle cost the company money while no value is being added for the customer. Defective parts cost money in materials, labor, and time because they either have to be replaced or reworked. Transportation is an area where money is being spent to move materials or parts, but no value is added for the customer. Any time a part is not being processed, it is said to be waiting. This costs money without adding value.

Material Supply

In order to produce products, manufacturers must have the necessary materials on hand. If a company keeps too much material in inventory, they are tying up money in purchasing and warehousing that material. If they run out of material, they risk having to shut down their operation. Companies keep a close watch on their supply inventories to balance between tying up too much money in materials and running out of materials.

Just-in-time (JIT) delivery systems allow for the delivery of parts and materials at exactly the time they are needed in production. JIT delivery cuts down on the costs of maintaining a large inventory, but it is a much more complex system to manage. See **Figure 14-23**.

Figure 14-23.

Just-in-time delivery helps decrease the amount of materials kept in stock. The materials arrive when they are needed and do not need to be housed for long periods of time.

Anton Gvozdikov/Shutterstock.com

Materials Handling

The movement of materials and products through a plant is often referred to as ***materials handling***. Materials must be moved from storage to each workstation in order and to storage on the other end. This can be done using conveyers, vehicles, or even by hand. Whatever the system, it must be efficient and not damage the materials being moved.

Quality Control

People want and deserve to get quality products. Consumers will continue to buy products from manufacturers they believe make quality products. This can be seen very clearly with automobile manufacturers. People usually buy cars based on what they perceive to be the highest quality for the money they are willing to spend. Manufacturers want to build quality products because they understand quality products will keep customers coming back. When products fail, customers return them. Returns are costly to manufacturers.

Quality control is a system whereby manufacturers ensure their products meet or exceed specifications. These specifications can pertain to size, shape, strength, performance, durability, and more. A good quality control program starts in the design of the product and follows that product through the manufacturing process.

Manufacturing engineers are responsible for the design and implementation of the quality control program. They develop quality standards based on customer requirements, train and motivate the workforce, ensure raw materials, parts, and products are being tested and meet standards, and minimize defects.

Materials and parts that are purchased by manufacturers are inspected for quality when they arrive at the plant. Building a product using substandard steel or with bolts of the wrong size will result in a product that fails quality control testing. Parts are inspected for quality throughout the manufacturing process. Parts that fail are discarded or reworked until they pass inspection.

Much of quality control centers on training and motivating the workforce. See **Figure 14-24**. Workers need to see the value in what they do, how it affects the overall quality of the products being produced, and their impact on the health and success of the company. Workers need to understand how to make quality products and what to do if a part or product fails testing. Workers must also be motivated to ensure quality in all they do. Workers are invited to discuss their ideas for quality with management. It is important that everyone be a part of the team.

Figure 14-24.

Workers must have proper training to perform quality control checks.

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Cost Control

Products must be produced for the specified price if the company is to be profitable. This is called ***cost control***. Costs can be controlled by controlling the resources used in the manufacture of products. Materials, machine time, and labor are all resources that can be controlled in manufacturing.

Materials can be wisely purchased and inventories can be effectively managed to control material costs. Accurate records and inventories must be kept to ensure efficiency.

Machines are a huge expense in manufacturing. Efficient scheduling of machine use can save costs by increasing production. Machines cannot be idle for long periods of time. Long runs of the same part are most efficient because no time is wasted changing the setup of machines. Engineers can examine the use of machines to make sure they are operating at the maximum acceptable speeds and that they are being loaded and unloaded efficiently.

Labor costs also need to be managed. Labor productivity can be defined as the output per hour. In manufacturing, this is the number of parts produced per hour. Manufacturing engineers can use time and motion studies to help decrease the amount of time it takes to perform a given task and improve efficiency. Time studies record the amount of time each task takes for each worker. Motion studies analyze the motions people and machines go through to perform given tasks. Manufacturing engineers then look for ways to decrease the motion to reduce time, fatigue, and wear and tear on equipment. They analyze workstations to make them as efficient as possible. They make sure all materials are as close as possible to the worker to decrease time and energy wasted. They make sure the workstations are suited for the workers who use them. For example, an extremely tall person might have a different workstation from a much shorter person.

Manufacturing engineers study every movement workers make to ensure there is no wasted or repetitive motion. They study worker fatigue and design work operations to make sure workers do not get too tired without proper rest. If a worker is too tired, he or she is less efficient and more likely to make a mistake or be injured. A good example of time and motion studies concerns shovel size. It was once believed that using a larger shovel would increase productivity. However, it was later found that a smaller shovel improved overall output because workers became too tired if the load was too heavy. Time and motion studies are used in all areas of work to increase worker productivity.

Safety

Safety programs are critical for many reasons. First and foremost, any responsible manufacturer values and wants to ensure the health and safety

of its employees. Another reason safety programs are important is cost. On-the-job injuries and deaths can cost manufacturers tremendous amounts of money. Fines for failing to comply with safety regulations can also be costly.

The US Occupational Safety and Health Administration (OSHA) was created as a result of the Occupational Safety and Health Act of 1970. OSHA's mission is "to ensure safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education, and assistance." All industries are required to follow OSHA regulations or face fines. State and local governments can also set safety regulations that must be followed.

Manufacturing engineers need to design the manufacturing process to ensure worker safety and health and are also responsible for compliance with safety regulation. Many companies also have employees who are solely responsible for managing the safety program.

Manufacturing Engineering in Action

You might wonder what kinds of specific projects manufacturing engineers might be tasked with handling or what types of problems they might be challenged with solving.

Imagine a manufacturing company has obtained a large contract to make dishwashers for at least the next few years. The company has purchased a large, empty building that it will use as its manufacturing facility. A manufacturing engineer might be tasked with determining how best to make this new product, how the facility should be laid out, what machines and tooling should be used, how the parts will flow through the plant, how each part will be made or if it will be purchased from a supplier, and what specific jobs each worker will perform.

The first decision is what type of manufacturing will be used. The manufacturing engineer could choose continuous manufacturing, intermittent manufacturing, or custom manufacturing. Because the company will be making large numbers of the same dishwasher for the foreseeable future, continuous manufacturing will best suit the company's needs.

The manufacturing engineer would then select the manufacturing operations. The engineer will decide how each part will be made based on the cost and efficiency of the available options. Operations are listed on an operation sheet. The engineer will decide what equipment and tooling will have to be purchased. Manufacturing engineers are often in charge of purchasing equipment so they can ensure it will meet their production and quality standards.

Once the operations have been determined, the manufacturing engineer would lay out the facility in the most efficient way possible based on the determined sequence of operations they have listed on the flow process chart for this particular dishwasher. This is an example of product layout because the facility is being designed specifically for the manufacture of one product. The goal is to minimize travel and storage time and to maximize efficiency based on the space available. The whole process must be designed from the storage of the raw materials, through each manufacturing process, to storage and distribution of the final product. All operations are listed on and studied using operations process charts. Manufacturing engineers communicate their plant layout designs in a variety of ways that can include CAD line drawings, 3-D CAD models, and 3-D physical models.

The manufacturing engineer would also be responsible for designing, implementing, and overseeing the quality control program to ensure the quality of the products being manufactured meets the standards determined by the company.

Every aspect of the new manufacturing process is laid out with cost, safety, and quality in mind. It is not enough to simply make dishwashers. They must be made in a way that is as profitable as possible, ensures a safe work environment for the workers, and delivers a product that meets quality standards.

Once the production line is up and running, the manufacturing engineer would constantly monitor all aspects of production and make improvements wherever possible.

Summary

- Manufacturing is the process of changing materials to make them more useful.
- The largest professional society for manufacturing engineers is the Society for Manufacturing Engineers (SME).
- Raw materials are gathered by drilling, mining, and harvesting. Each technique has specific uses and applications.
- Raw materials are processed into standard stock through primary processing.
- Standard stock materials are made into useful products through secondary processing. Common secondary processing techniques are separating, casting and molding, forming, and combining.
- Manufacturing engineers design all aspects of production from start to finish. They must understand all characteristics of the product(s) to be made and all specific requirements.
- The three types of manufacturing systems are continuous, intermittent, and custom.
- Plant layout refers to the location of the materials that will be made into products and how they are moved through the plant, including such aspects as equipment layout, utility location, and traffic flow. Most plants are designed using either process layouts or product layouts.
- Manufacturing engineers create systems to ensure all products are produced correctly. These systems include material supply, materials handling, quality control, and cost control.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is *manufacturing engineering*?
2. What level of education is required to become a manufacturing engineer?
3. The drilling process is *not* used to gather _____.
   A. natural gas
   B. uranium
   C. oil
   D. water
4. What are the two types of mining?
5. Which type of harvesting leaves a certain amount of large trees per acre so the forest will regenerate naturally?
   A. Clear-cutting.
   B. Selective cutting.
   C. Seed tree cutting.
   D. Reclamation.
6. Trees being cut into lumber is an example of _____ processing.
   A. primary
   B. secondary
   C. separating
   D. standard stock
7. Which of the following processes changes the shape of materials through compression, bending, or stretching?
   A. Separating.
   B. Casting and molding.
   C. Forming.
   D. Combining.
8. The most common _____ technique is welding.
9. _____ manufacturing is used to produce a single product or a small number of products.
10. Small batches of parts move together through a factory in _____ manufacturing.
11. _____ manufacturing produces the highest number of parts at the lowest cost in plants that are specifically designed to produce these parts.

12. What is the difference between jigs and fixtures?
13. _____ layout is commonly used for continuous manufacturing.
14. What are the pros and cons of just-in-time (JIT) material delivery systems?
15. What are the three resources that must be controlled in order to control costs?

Reinforce *learning*

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
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Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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Chapter 15

Chemical Engineering

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Objectives

After studying this chapter, you should be able to:

- Define *chemical engineering*.
- Compare and contrast chemistry and chemical engineering.
- Explain the laws of thermodynamics and how they are used in chemical engineering.
- Explain how mass balance is used to analyze chemical processes.
- Describe fluid dynamics and its effect on chemical engineering.
- Discuss different types of measurement used in chemical engineering.
- List and explain the factors a chemical engineer might consider when designing a chemical plant and choosing a site.
- Describe OSHA and its goal to keep workers and community members safe from exposure to hazardous chemicals.

Key Terms

absolute pressure
American Institute of Chemical Engineers (AIChE)
aneroid gauge
batch chemical plant operations
bimetallic temperature measurement device
bioplastics
block flow diagram
Bourdon-style pressure gauge
change-of-state temperature measurement device
chemical engineering
chemistry
clean coal
coal gasification
continuous chemical plant operations
differential balance
differential pressure flowmeter
entropy
first law of thermodynamics
fluid dynamics
fluid flow
Garbage Patch
gauge pressure
gyre
infrared temperature measurement device
integral balance
laminar flow
liquid column gauge
mass balance
mass flowmeter
material safety data sheets (MSDS)
mechanical flowmeter
Occupational Safety and Health Administration (OSHA)
open-channel flowmeter
piping and instrumentation diagram
plant layout
pressure
process flow diagram
resistance temperature measurement device
"right to know" laws
second law of thermodynamics
site layout
surface tension
thermocouple sensors
thermodynamics
turbulent flow
velocity flowmeter
viscosity
waste
Zeroth Law

Practice vocabulary

Chemical engineers have improved our lives in countless ways. Chemical engineers have helped to provide the energy that powers our world, improved the quality of the food we eat, made our electronic devices smaller and faster, provided clean drinking water, cleaned up our waste, created new materials, provided countless advancements in medicines and medical treatments, and lead the charge for clean and sustainable energy sources.

Look around you. Most of the products you see are the result of chemical engineering. Chemical engineers are constantly developing new and better products to meet our needs, improve our lives, conserve our natural resources, and combat global warming. See **Figure 15-1**. Sometimes they develop new materials like Kevlar™. Kevlar™ has incredible strength for its weight and is used in such products as bulletproof vests, fiber optic cables, bridge construction, and airplane and bridge reinforcement. This is just one example of how chemical engineers can improve and even save lives.

Chemical engineering is the branch of engineering that deals mostly with the large-scale production of chemical products. Chemical engineers are responsible for the invention of new processes and the design, construction, and operation of facilities that create products on a large scale. Chemists usually work in a laboratory with chemicals on a small scale. Chemical engineers usually work with large-scale production of chemicals and chemical products. Chemists often create chemical reactions, and chemical engineers make these reactions economical and safe on a large scale.

Many chemical engineers are employed in the petroleum industry refining and processing petroleum into a wide variety of useful products, **Figure 15-2**. But they also produce medicines, electronics devices and components, plastics, paper, food products and additives, sustainable energy products, synthetic materials, and biomedical products.

All engineers use their technical knowledge to solve problems to improve our lives and save our environment. Chemical engineers call on their extensive backgrounds in chemistry and science to solve problems dealing with chemicals, other materials, and large-scale production.

Figure 15-1.
The work of chemical engineers went into this vehicle in the development of the materials and fuel cell.

Jose Gil/Shutterstock.com

Figure 15-2.
Many chemical engineers work in petroleum refineries or with petroleum in some other way.

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History

Chemical Engineering in History

The earliest chemical engineers were actually chemists by education, but they used their chemistry backgrounds to develop large-scale production systems to make chemicals. Chemical engineering as a course of study at the university level did not start until 1888. It grew out of chemistry departments who saw a need to apply the chemical knowledge they had gained.

In 1937, Margaret Hutchinson Rousseau became the first woman to earn a doctorate degree in chemical engineering from the Massachusetts Institute of Technology (MIT).

As a young chemist during World War II, Rousseau worked on two extremely important projects. These were the large-scale production of penicillin and the development of high-octane fuels.

Penicillin is used to treat a variety of infections caused by bacteria. Penicillin production could not keep up with demand because it was being grown in flasks and pans in the laboratory. Margaret Hutchinson Rousseau is credited with the discovery of deep tank fermentation, where deep tanks with thousands of gallons of capacity were used to grow mold. The mold had to be kept at a constant temperature and stirred constantly to provide oxygen to the mold. The process by which the penicillin was extracted from the mold also had to be scaled up to massive proportions. Because of her breakthroughs, enough penicillin was produced to treat people at home and on the warfront. Many lives were saved on the warfront because infections could be treated with penicillin.

Margaret Hutchinson Rousseau also developed new techniques in petroleum distillation. She was able to make higher-octane fuels that were used on the warfront. High-octane aircraft fuel meant higher fuel efficiency and more power. She also produced products like antifreeze and pure acids that were used in the manufacture of rubber, plastics, and pharmaceuticals.

She went on to be the first female member of the American Institute of Chemical Engineers (AIChE). In 1983, she earned the Founders Award, which is the highest award the AIChE gives.

Professional Aspects

The requirement for an entry-level chemical engineer is a bachelor's degree in chemical engineering. For higher-level positions, master's degrees or doctorate degrees are usually required. To earn a degree in chemical engineering, courses must be taken in math, science, materials, technology, and engineering.

Many colleges and universities offer two-year associate's degrees programs that can lead into four-year chemical engineering programs or qualify graduates for jobs as chemical technicians. Chemical technicians often operate and maintain chemical equipment, conduct research, manage hazardous chemicals, analyze samples, and perform other duties in the chemical industry.

In order to be accepted into a chemical engineering program, students should earn the best possible grades in high school. Students should plan to take a minimum of one year of biology, one year of chemistry, one year of physics, and math through calculus.

The broadest professional society for chemical engineers is the ***American Institute of Chemical Engineers (AIChE)***, with nearly 40,000 members in more than 93 countries. There are other professional societies that support specific areas of chemistry and the chemical industry, but the AIChE is specifically dedicated to the field of chemical engineering.

Chemical Engineering Principles

The following principles of chemical engineering dictate the way in which chemical engineers design, study, and troubleshoot chemical operations. Chemical engineers must have a firm understanding of these principles in order to be successful.

Chemistry

Chemistry is the scientific study of materials, their properties, their interactions, and the changes that they undergo. Atoms are the smallest individual microscopic particles of matter. Molecules are two or more atoms held tightly together. See **Figure 15-3**.Chemistry is the study of chemical reactions that occur between atoms and molecules. Chemistry is the study of material composition, structure, and properties.

Chemistry is often referred to as the "central science" because it is so important in all areas of science and other areas. Chemistry prepares students for daily life as well as careers in the sciences and many other fields including research, medicine, engineering, economics, and law.

Chemistry is all around us. Understanding chemistry means understanding our world.

Thermodynamics

Thermodynamics is the study of work, energy, and efficiency in large-scale systems. It first originated in the development of steam engines. Thermodynamics can be used to study the change of energy into work and heat. For example, think of an electric drill motor. Energy in the form of electricity is changed into work in the form of rotational motion and heat. The main laws of thermodynamics are used to predict the operation of systems.

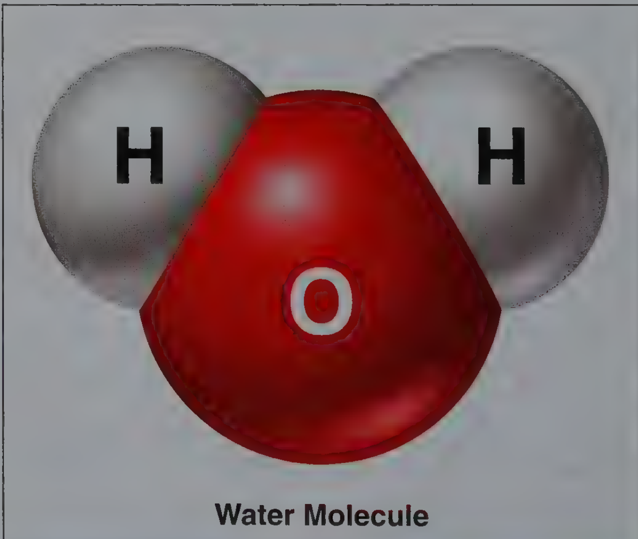

Figure 15-3.

Atoms are the smallest particles of matter. Molecules are made up of at least two atoms. One water molecule contains two hydrogen atoms and one oxygen atom.

Lightspring/Shutterstock.com

Chemical Compounds

Elements make up matter. The combination of elements is called a compound. Compounds are unique. The characteristics of the elements that make up a compound can be entirely different from the characteristics of the compound itself. A compound is a completely different kind of material from the elements that create it.

The atom of an element contains a certain number of electrons distributed in shells. To create a compound, the electron or electrons in the outermost shell of an atom either transfers to or combines with the electron or electrons in the outermost shell of another atom. A compound formed by transferring an electron is typically an ionic compound. A compound formed by sharing electrons is a covalent compound.

Compounds are also different from each other because of the amounts of each element that goes into them. For example, carbon dioxide will always be CO_2. The proportion, or ratio, of two atoms of oxygen for every one atom of carbon will always exist for carbon dioxide. Putting carbon and oxygen together won't create carbon dioxide unless the proportions stay the same.

First Law of Thermodynamics

"The change of the internal temperature of a system is equal to the heat added to the system, minus the work done by the system."

The ***first law of thermodynamics*** is an application of the law of conservation of energy, which states that energy cannot be created or destroyed. The amount of energy in a closed loop remains constant. In other words, energy can change forms, but it cannot be created or destroyed. An electric drill motor uses all the energy that flows to it. Some energy is transferred into motion and some is wasted as heat, but it is all changed to another form and is not destroyed.

The law states that change in internal energy (U) in a system equals the heat added to the system (Q) minus the work done (W). This can be shown as:

$$\Delta U = Q - W$$

Think of a gas trapped in a cylinder below a piston, **Figure 15-4**. If the gas is heated, Q increases. If pressure is held constant while the heat is added, the gas will expand and move the piston, and W (work) is done by the piston.

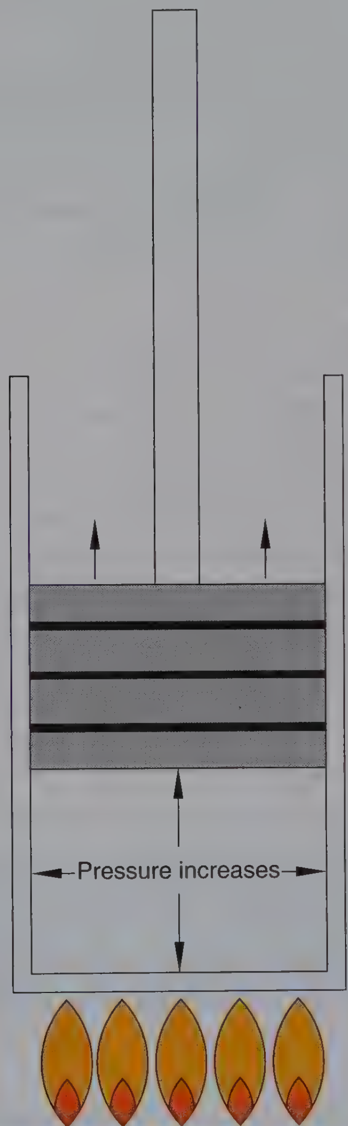

Figure 15-4. Expand learning

The heat in this piston causes the gas to expand and move the piston.

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If the piston is pushed down, W becomes positive because energy was added to the system in the form of heat through compression of the gas.

As heat is added, the gas expands and moves the piston. You can calculate the amount of upward force on the piston if you know the pressure and the size of the piston. Pressure is commonly measured in pounds per square inch (psi). Imagine we have 10 psi of pressure and a 4″ diameter piston. The first step is to find the surface area of the piston.

The formula to find the area of a circle is equal to pi (π) multiplied by the radius of the circle squared. Radius is half the diameter. We will round pi to 3.14.

$$A = \pi \times r^2$$

$$A = 3.14 \times 2 \times 2$$
$$A = 3.14 \times 4$$
$$A = 12.56 \text{ in}^2$$

The force of 10 psi is acting on 12.56 in^2 of surface area. Piston force can be calculated by multiplying pressure by the area of the piston.

$$10 \text{ psi} \times 12.56 \text{ in}^2 = 125.6 \text{ pounds of force}$$

Second Law of Thermodynamics

"Energy flows from areas of high concentration to areas of lower concentration."

The ***second law of thermodynamics***, often called the entropy law, is concerned with the idea that concentrated sources of energy will naturally disperse. ***Entropy*** can be defined as the tendency of all energy and matter to seek a state of uniformity. Think of a hot cup of coffee sitting on a table in a cool room. The energy from the coffee (in the form of heat) immediately starts to disperse into the room until air in the room and the coffee reach the same temperature. The same is true of a bicycle or car tire. If the tire runs over a nail and a small hole is made, the higher-pressure air inside the tire will leak out until the air inside of the tire and outside of the tire reach the same pressure.

One could say that the natural tendency of things is downhill. Concentrations of energy tend to dissipate. Things that are hotter than their surroundings tend to cool. Things that move tend to slow down and stop. Things that were once living tend to decay. Water tends to flow downhill, and voltages tend to decrease. That is all true, unless energy is added. Hot coffee will stay hot if it is left on a heat source. Naturally growing things like trees do not decay while they are alive because they create their own energy. A bicycle will keep moving if the rider adds energy by peddling. We can increase concentrations of energy by adding energy.

We can also use the second law to our advantage. In power plants that generate electricity through heat, water is heated until it creates steam under great pressure. Remember that this pressure naturally wants to neutralize itself. The steam is then allowed to expand across turbines. This causes the turbines to spin, which rotates a shaft and turns the generator to generate electricity. See **Figure 15-5**.

Third Law of Thermodynamics

"Entropy approaches zero as temperature approaches absolute zero (–273.15°C, –459.67°F, or 0 K)."

The energy level of an object is determined by how much its atoms move. The colder an object gets, the less its atoms move. At temperatures near absolute zero, almost all atomic movement stops. Because energy is near zero, entropy is also near zero.

To better understand the third law of thermodynamics, think of water, which exists in nature as a gas, a liquid, and a solid. In its gas state, its atoms move around freely, and its entropy is very high. In the liquid state, its atoms move around less freely, and entropy decreases. In the solid state, molecules are packed together very tightly and move very little, so entropy is low.

Zeroth Law

The ***Zeroth Law*** is an observation dealing with thermodynamic equilibrium. Thermodynamic equilibrium is the state at which two or more objects are in the same state. Physical properties of matter can change when their temperatures change. For example, copper has a positive temperature coefficient. This means that as the temperature of copper wire increases, its resistance increases and its conductivity decreases. As the temperature of a gas in an enclosed container increases, its pressure also increases.

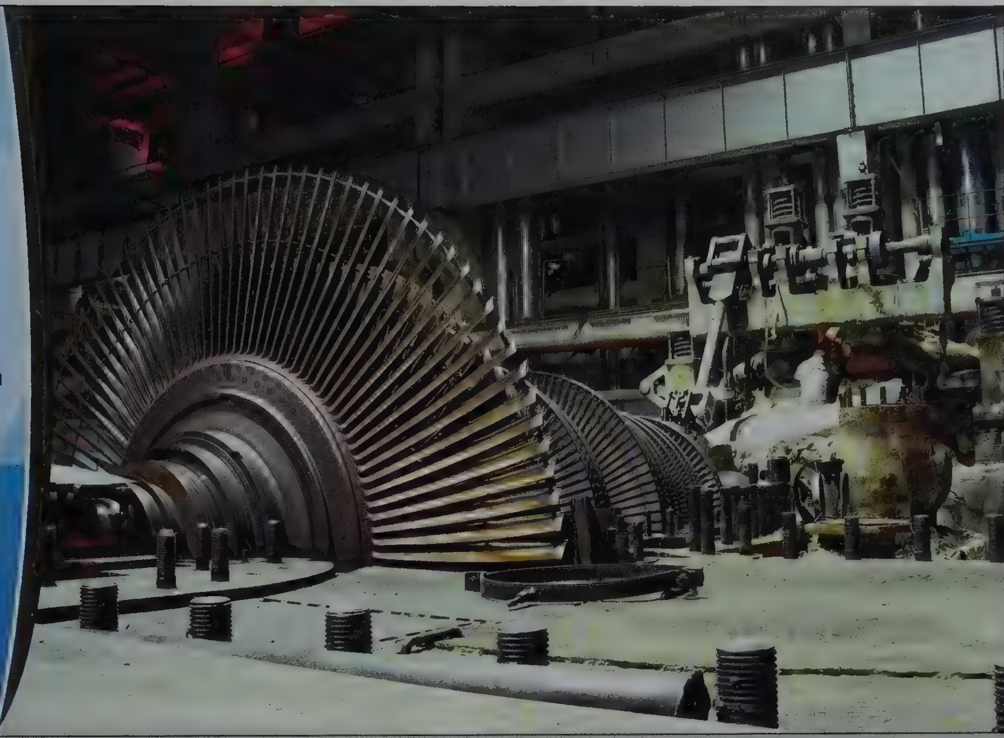

Figure 15-5.
Steam is used to generate electricity with the second law of thermodynamics. First, steam is created in order to spin turbines. Then, the turbines can turn a generator to generate electricity.

Arogant/Shutterstock.com

When two objects come in contact with each other, there is a change in their properties if they are at different temperatures. Over time, their temperature balances out, and they are in a state of thermodynamic equilibrium.

The Zeroth Law states that when two objects are separately in thermodynamic equilibrium with a third object, they are in thermodynamic equilibrium with each other. Picture three blocks of metal lying next to each other, **Figure 15-6**. The two on the outside are in contact with the one in the middle, but they are not in contact with each other. Because each of the outside blocks is in thermodynamic equilibrium with the one in the center, the two on the outside would be in thermodynamic equilibrium if they were brought together.

An example of the Zeroth Law is the mercury thermometer. As the temperature changes, so does the length of the column of mercury inside of the thermometer. Thermometers are calibrated on several points along the scale using known quantities like freezing and boiling. That way, when the thermometer is used to measure something else, such as body temperature, it can be assumed accurate.

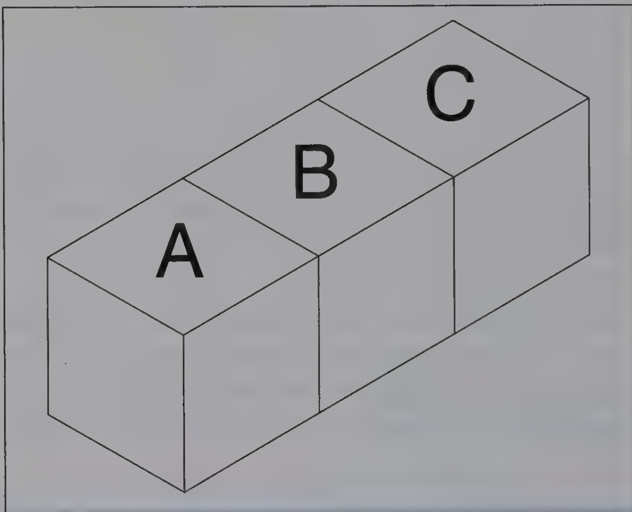

Figure 15-6.
According to the Zeroth Law, if the two outer blocks are both in equilibrium with the middle block, then they are also in equilibrium with each other.

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Mass Balance

Chemical engineers use the concept of mass balance to study and evaluate chemical processes. ***Mass balance*** is founded in the law of the conservation of matter, which states that matter cannot

be created or destroyed and, therefore, must be constant in a closed loop (no means for chemicals escaping). The amount of material that exists prior to a chemical reaction is equal to the amount of material after the reaction has taken place.

Chemical reactions occurring in chemical plants often require multiple streams of different feed materials going into the reaction and multiple streams of final product or by-product coming out. A mass balance is done for every stream. Assuming that there is no accumulation of mass inside of the process, a simple mass balance equation can be expressed as:

Input = Output *or* Total mass in = Total mass out

For example, think of a separating process where a slurry of water and gravel is being separated, **Figure 15-7**. The slurry contains an equal mass of water and gravel. Gravel weighs 105 lb/ft^3, and water weighs 8.3 lb/gallon. We can find how many gallons weigh the same as one cubic foot of gravel by dividing the weight of a cubic foot of gravel by the weight of a gallon of water.

105 lb gravel ÷ 8.3 lb water = 12.65 gallons water per cubic foot of gravel

For every cubic foot of gravel that goes in, it must be matched with 12.65 gallons of water to ensure equal mass of water and gravel. You can see this as a 1:1 ratio.

To perform a mass balance test, you could measure the water and gravel coming out to make sure they are leaving the separator at the same mass per time.

There are two kinds of mass balances that are taken: differential and integral. ***Differential balances*** are taken at the same point over time. In a continuous process, they should read the same every time. ***Integral balances*** are taken at two different points to show what is happening between one point and another. It is typically taken at the beginning and end of a process.

Fluid Dynamics

Fluid dynamics is the study of ***fluid flow***, or liquids and gases in motion. Fluid dynamics is important to chemical engineers because so much of what they do deals with fluids flowing through pipes from one place to another. This can occur in a chemical plant or in a pipeline that carries something like drinking water or crude oil for great distances. Most fluid dynamics examination deals with velocity, pressure, density, and temperature.

Viscosity is the thickness of a liquid, or its resistance to being deformed. Oil is thicker than water, so oil has a higher viscosity than water. Viscosity is extremely important because the viscosity of a liquid has a significant impact on its flow rate. Viscosity is measured using a viscometer. Zahn cups are commonly used to measure the viscosity of paint. Picture a cup with a small hole in the bottom. The cup is filled with paint. The time it takes for the cup to drain is called *efflux time* and corresponds to viscosity.

Many chemical products, such as motor oil, have to be made to meet strict viscosity specifications. Motor oil is rated using the Society of Automotive Engineers (SAE) rating system.

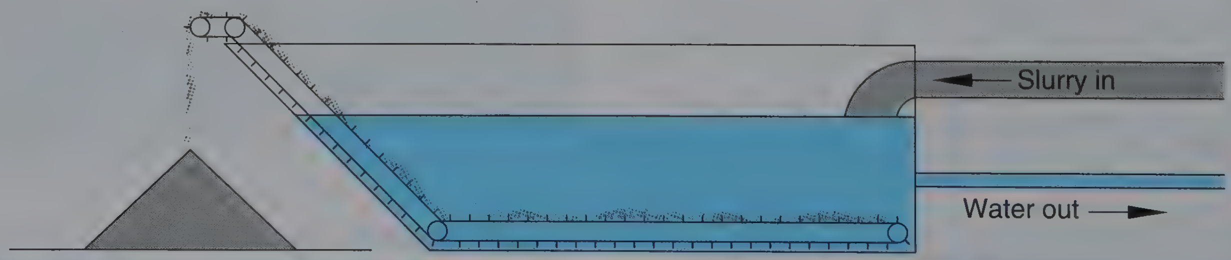

Figure 15-7.

Separating water from gravel in a slurry is an example of finding mass balance. The total amount of slurry equals the water plus the gravel.

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Lower numbers indicate thinner oil that will flow more easily and higher numbers indicate thicker oil. For example, 10-weight motor oil is thinner than 30-weight oil. A common rating for modern motor oil is 5W-30. The W indicates winter and indicates viscosity at 0°F (–18°C). The other number indicates the high temperature viscosity at 210°F (99°C). On a day when it is 0°F (–18°C) and the engine is cold, the oil will act like 5-weight oil when the engine is started and 30-weight oil when the engine reaches operating temperature. Viscosity modifiers are additives used to keep oil thin under extreme cold but also to keep it thick to protect engine parts when temperatures are high.

Surface tension is created because the molecules of a liquid usually tend to be more attracted to each other than they are to their surrounding materials. This creates a characteristic almost like a film on the surface. Have you ever poured a glass so full that the water was actually higher than the rim of the glass? Why did the water not run over the edges? Why can the pond skater insect in **Figure 15-8** stand on top of the water? The water molecules are more attracted to each other than they were to the glass or the air. The same is true of a dripping faucet. Notice that water accumulates under the faucet until the drop gets heavy enough that gravity pulls it away from the other water molecules.

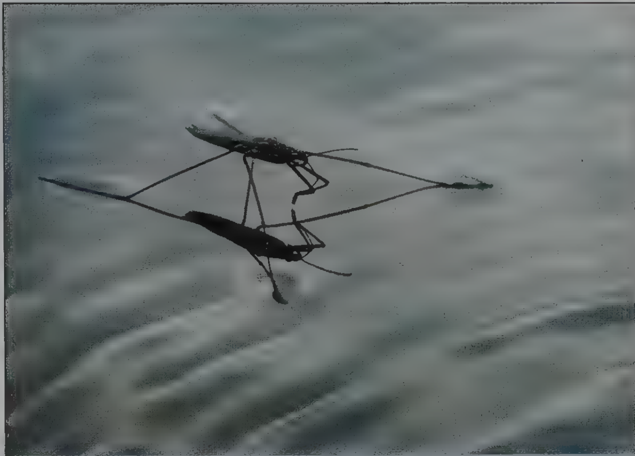

Figure 15-8.

The water molecules hold together to allow the insect to stand on top of the water. This is the water's surface tension.

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Fluid flow can be characterized in one of two broad flow regimes: turbulent and laminar. See **Figure 15-9**. Think about what happens if you drag your hand through the water in a pool or bathtub. The water behind your hand swirls and mixes. This is ***turbulent flow***. The swirls you see in the water are called eddies. ***Laminar flow*** is when there is no disruption between the layers of fluid, and there are no eddies or changes in the fluid. Think of fluid flowing through a pipe. In turbulent flows, fluid particles flow in many directions with no observable paths or layers. In laminar flow, there is little or no mixing and the particles flow in straight streamline paths. Flow regimes are characterized by their Reynolds Number, which expresses the ratio of inertia to viscosity. Inertia is the resistance of a material to change its state of motion. Fluid flow with a Reynolds Number under 2,000 is said to be laminar and fluid flows over 4,000 are said to be turbulent. Flows between 2,000 and 4,000 are said to be in a transitional area. You can imagine how important these calculations

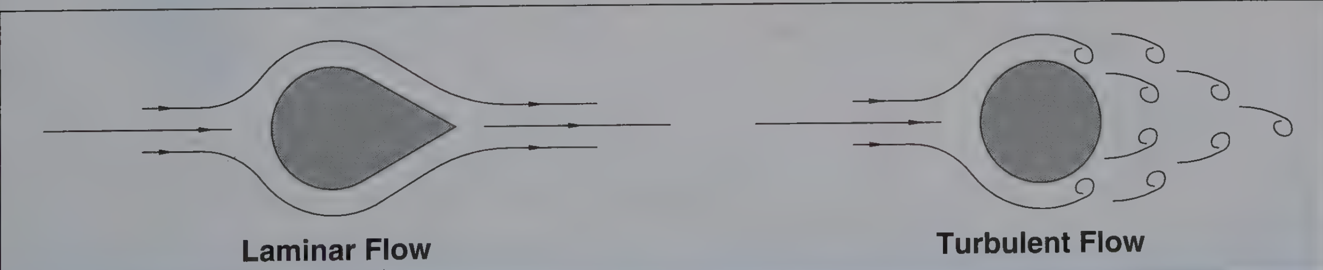

Figure 15-9.

Laminar flow is a smooth fluid flow. With turbulent flow, the water swirls and mixes as it flows.

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are to a chemical engineer who is designing a pipeline or other fluid transport system because they would want to create the most efficient systems possible. As turbulence of flow increases, so does the amount of energy it takes to move that fluid.

Characteristics and Measurements

Chemical engineers often design chemical operations to happen on large scales like those in chemical plants. They also monitor these large-scale reactions. Throughout the design phase and the constant monitoring of chemical operations, it is crucial to measure flow rate, pressure, and temperature.

Fluid Flow Rate Measurement

Fluid flow rate is measured using a variety of specific metering devices called flowmeters. These devices measure the amount of flow per unit time. For example, you could measure gallons per minute. A simple measurement method is using a container of known size and a timer. Place an empty one-gallon jug under your sink and time how long it takes to fill that jug. Imagine it takes 20 seconds to fill the one-gallon jug. Based on that measurement, you now know that the flow rate at your sink is three gallons per minute.

However, in industrial settings, it is difficult to measure flow that simply. So, flowmeters must be used. Some common types of flowmeters are listed and explained below. See **Figure 15-10**.

Differential pressure flowmeters rely on Bernoulli's principle. Bernoulli's principle states that as the speed of a fluid increases, its pressure decreases. Differential pressure flowmeters constrict the flow by placing some sort of obstruction inside of a pipe or by narrowing the pipe at a point. As the fluid goes around the obstruction or through the narrow point, it speeds up and its pressure decreases. Flow rate is determined using the pressure at the obstruction, or narrow point, and away from that point. See **Figure 15-11**.

Velocity flowmeters measure the speed of passing fluid and the depth of the fluid. If the area inside of a pipe is known, the area combined with the speed of the fluid can be used to determine flow rate. Velocity flowmeters can also be used on airplanes to measure speed relative to the air.

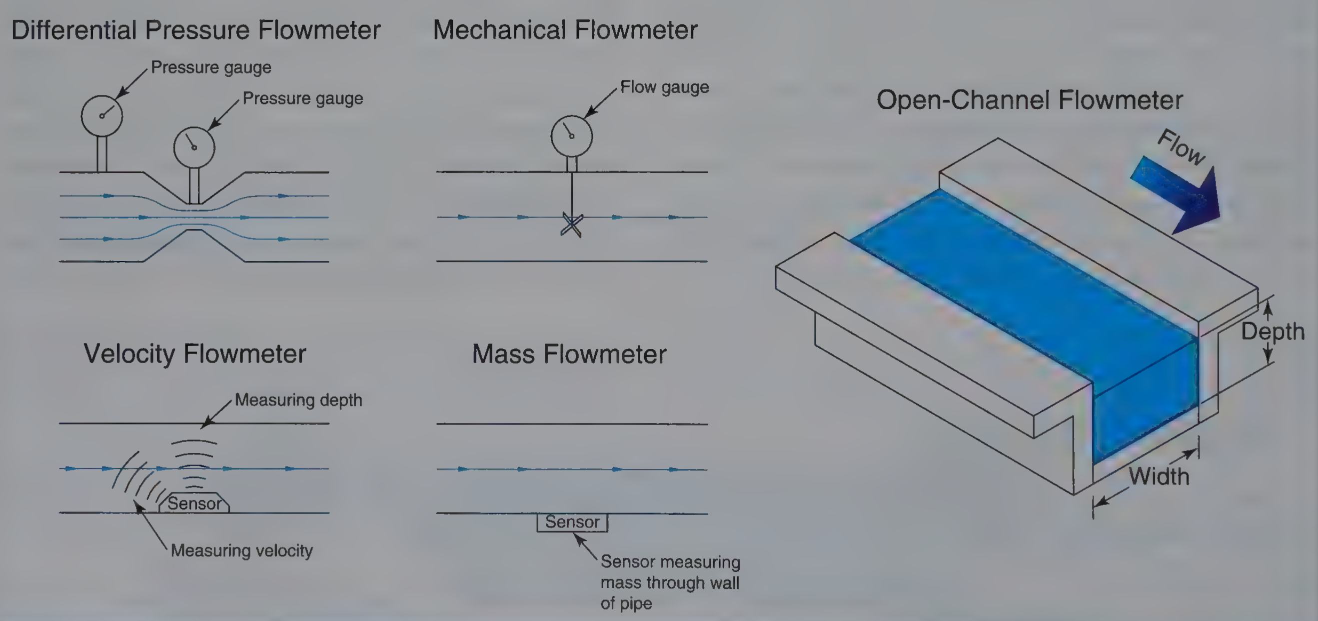

Figure 15-10.

Common types of flowmeters include differential pressure flowmeters, velocity flowmeters, mechanical flowmeters, mass flowmeters, and open-channel flowmeters.

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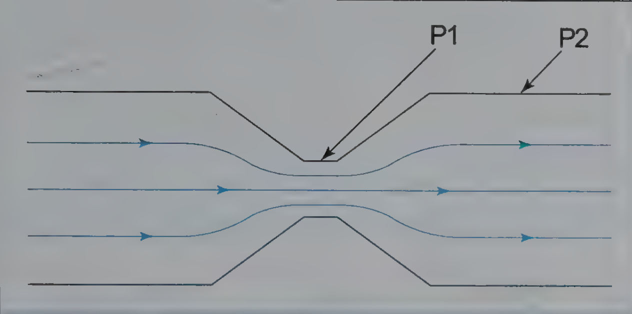

Figure 15-11.

Differential pressure flowmeters measure flow rate by taking measurements at the narrow point and away from that point.

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Let's say you want to determine the flow rate in gallons per minute of a pipe with a 4″ inside diameter that is full of water moving at a velocity of 30 in/s. The flow rate (F) is the product of the cross-sectional area (A) and the velocity (V).

The first thing we need to do is use the known pipe diameter to find the cross-sectional area in square inches. Area of a circle is found by multiplying pi (3.14) by the square of the radius.

$$A = \pi r^2$$
$$A = 3.14 \times 2 \times 2$$
$$A = 12.56 \text{ in}^2$$

Now we can calculate flow.

$$F = A \times V$$

$$F = 12.56 \text{ in}^2 \times 30 \text{ in/s}$$
$$F = 376.8 \text{ in}^3\text{/s}$$

There are 231 in^3 of liquid per gallon.

$$\text{Gallons} = \text{cubic inches/231}$$
$$= 376.8 \text{ in}^3\text{/231}$$
$$= 1.63 \text{ gallons}$$

Your 4″ pipe, moving water at a velocity of 30 in/s, is passing 1.63 gallons of water every second.

Mechanical flowmeters use a variety of mechanical devices inside of a pipe to measure flow. One example is an impeller, which looks something like a fan blade. Picture an impeller inside a pipe. It is known how much flow it takes to make one revolution of the impeller. The number of rotations per unit of time is recorded and the flow rate is known.

Mass flowmeters measure the mass rather than the volume. They are particularly valuable when measuring gases because the volumes of gases can vary greatly depending on temperature.

Open-channel flowmeters measure the flow in a channel rather than in a pipe. Picture a stream or a river. If the cross-sectional area of the stream bed is known and the speed of flow is measured, then the flow rate can be determined.

Pressure Measurement

Pressure is another crucial measurement in chemical operations. If pressures are not held within acceptable ranges, products can fail to meet quality standards. If pressures get too high, catastrophic accidents can occur.

Pressure is measured by force per unit area. For example, pressure in car tires is usually listed as pound per square inch (psi). If a car tire is inflated to 30 psi, then there are 30 pounds of force pressing against each square inch of the inside of the tire in all directions. See **Figure 15-12**. The most common types of pressure measurement are gauge and absolute. In most cases, like in the example of the car tire, the gauge pressure is used. ***Gauge pressure*** is the measurement of pressure relative to the atmospheric pressure.

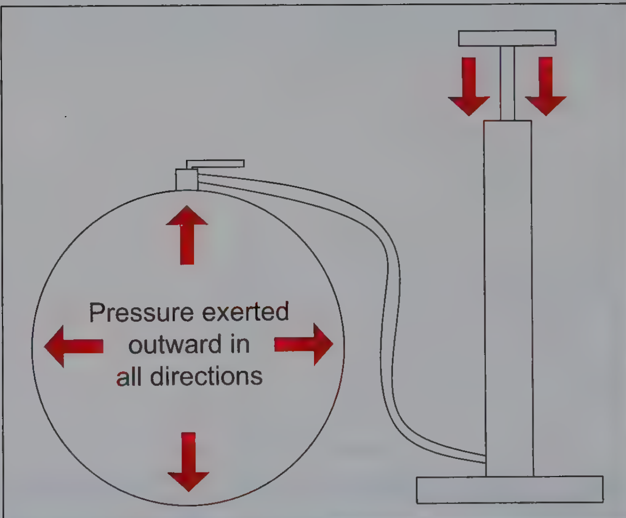

Figure 15-12.

When filling a ball with air, the pressure is exerted outward. If you pump a basketball to 7.5 psi, then 7.5 pounds of force are exerted in all directions.

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Absolute pressure is the pressure relative to a vacuum. Absolute pressure is gauge pressure plus the local atmospheric pressure. Some common types of pressure meters are listed and explained below. See **Figure 15-13**.

Liquid column gauges use a fluid in a tube, **Figure 15-14**. One end is connected to the pressure to be measured, and the other is exposed to a control pressure, which could be atmospheric pressure or a vacuum.

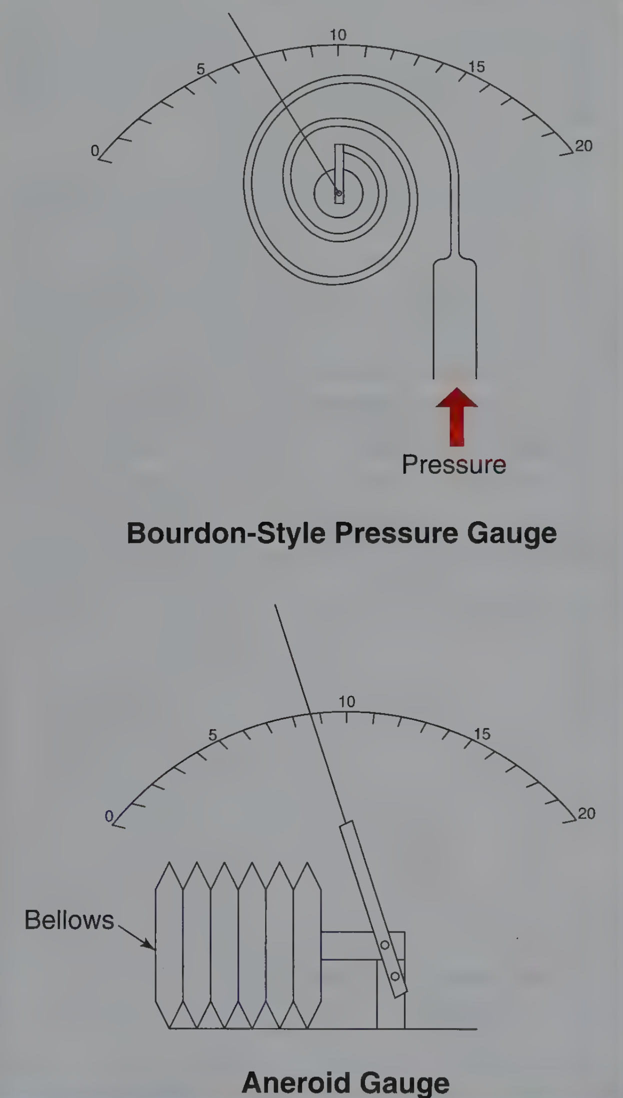

Figure 15-13.

In a Bourdon-style pressure gauge, as the pressure increases, the coil starts to unwind, moving the needle. As pressure changes in an aneroid gauge, the bellows expands and contracts, moving the needle.

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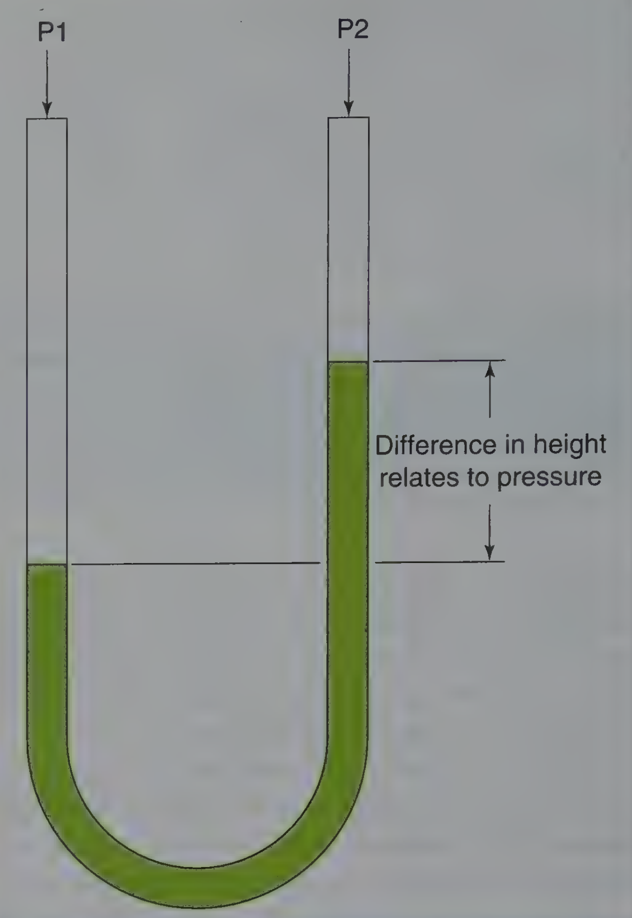

Figure 15-14.

In this liquid column gauge, a control pressure is pumped into the P2 end, and the pressure from P1 can be measured.

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Bourdon-style pressure gauges use coils of tubing. The shape of the coil changes in relation to the pressure changes. The coil is connected to the needle through a mechanical linkage. As the pressure changes, the needle moves.

An ***aneroid gauge*** uses a small bellows (like an accordion) that changes shape as pressure changes. It expands as pressure decreases and contracts as pressure increases. The bellows is connected to the gauge needle. When the needle moves, the size of the box changes.

There are also a wide variety of electronic pressure gauges. These use magnetism, optics, capacitance, and other techniques to measure pressure.

Temperature Measurement

Temperature is another critical measurement for chemical engineers. Many chemical reactions can only occur within certain safe and acceptable temperature ranges. Because temperature and pressure are so closely connected, too much variation in temperature can have serious consequences.

Several devices are used to measure temperature. ***Thermocouple sensors*** are made from two different pieces of conductive material. As the temperature of the thermocouple increases, it creates a voltage. This voltage can be measured to determine the temperature, **Figure 15-15**.

Thermocouples are commonly used as safety devices in gas appliances, such as heaters. Many gas appliances have a pilot light burning. A pilot light is a very small flame meant to ignite the gas when the heater turns on. Imagine the pilot light is not on. The thermostat calls for heat, the heater opens the gas valve, and the gas does not burn because the pilot light is out. The building could fill up with gas, which would be extremely dangerous. To avoid this, thermocouples are placed next to the pilot light. As long as the thermocouple is sending voltage, the heater knows the pilot light is lit. If it stops sending a voltage, it means the pilot light is out, and the heater will not open the gas valve.

Resistance temperature measurement devices rely on the concept that resistance, or conductivity of a conductor changes as temperature changes.

Infrared temperature measurement devices measure the thermal radiation emitted from a material. This is done from a distance. There is no need to directly contact the material to the device. This can be useful when dealing with caustic materials.

Bimetallic temperature measurement devices rely on the concept that different metals expand and contract due to temperature at different rates. Strips of unlike metals are joined together. As temperature changes, the strips will bend. The bending action correlates to temperature. See **Figure 15-16**.

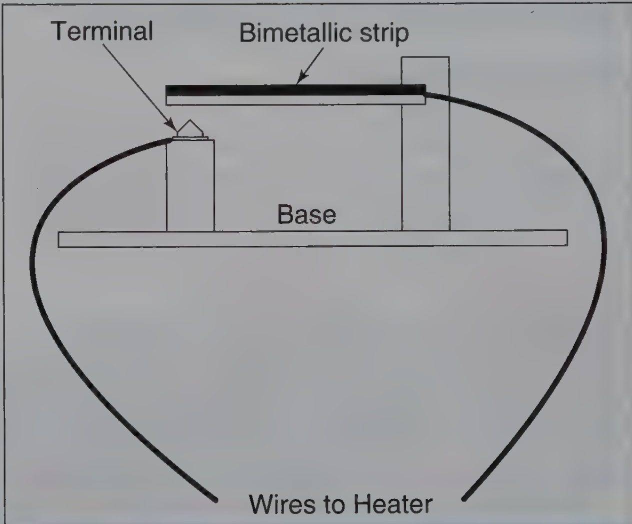

Figure 15-16.
The bimetallic strip will bend when it reaches a particular temperature.

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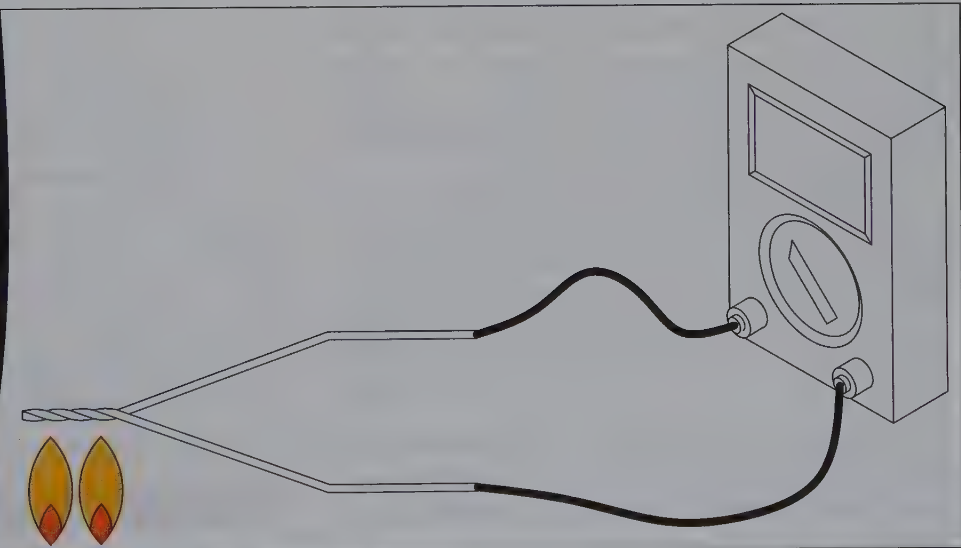
Figure 15-15.
Thermocouple sensors are used to measure temperature in relation to voltage. The voltage measurement is used to find the temperature.



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Change-of-state temperature measurement devices are usually made into stickers or labels. When they reach a certain temperature, they permanently change colors. These are commonly used when there are legal concerns related to temperature. For example, they could be placed on a case of seafood in transport to ensure it never went above a certain temperature. If it did at any point in the process, the label would have permanently changed and the buyer would know the food was spoiled.

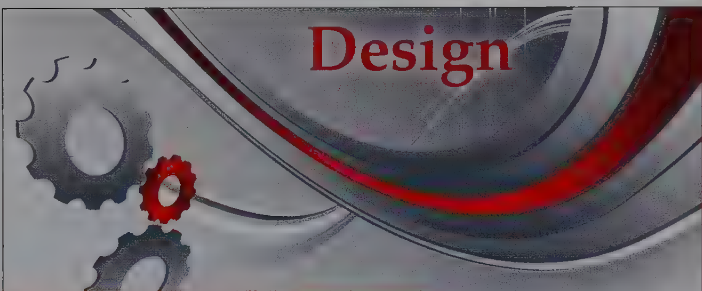
Chemical Engineering Applications

Some chemical engineers create new chemical processes and products, but most plan and operate chemical plants, wastewater treatment facilities, biomedical facilities, food and beverage facilities, and power plants. In their management of these facilities, chemical engineers are often responsible for the design of the facility, operations, the economics involved, the chemical reactions and processes, safety, environmental considerations, management, and more.

Much like manufacturing plants, which are discussed in Chapter 14, there are two main types of chemical plants: continuous and batch.

In ***continuous chemical plant operations***, materials are fed into the facility, reactions occur, and materials are fed out of the facility constantly. See **Figure 15-17**. The facilities can continue the same chemical processes around the clock without stopping. For large-scale chemical operations, such as the refining of petroleum, continuous operations are the most efficient and economical.

In ***batch chemical plant operations***, chemicals are fed into the system, the chemical process



Chemical Symbols

At first glance, a piping and instrumentation drawing looks a lot like a schematic drawing for an electrical circuit. An electrical circuit contains the source of electricity, the load or loads that use the electricity, control devices and components (such as resistors, diodes, and transistors), meters, protection devices (such as fuses and circuit breakers), and the conductors that connect them together.

Drawings of chemical facilities are not that much different. They include the sources of chemicals, any pumps needed to move the chemicals, the pipes that direct flow from one place to another, pressure gauges, flowmeters, mixers and separators, heaters and coolers, holding tanks, and the final location of each product.

Chemical engineers and technicians learn to use symbols to represent components of the drawings, in the same way electrical engineers learn to use symbols in schematic drawings. See **Figure A**.

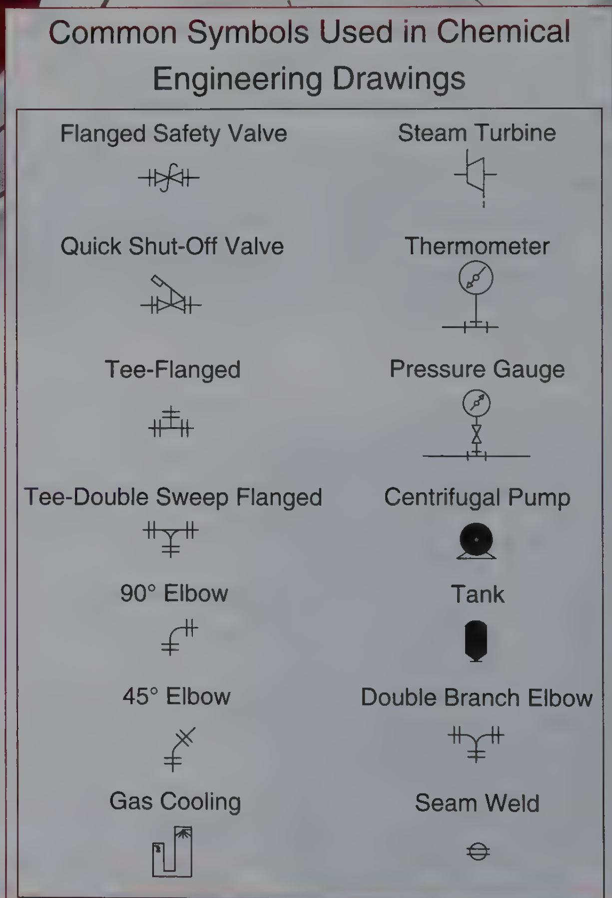


Figure A

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Figure 15-17.

In a facility that makes sports drinks, continuous chemical plant operations can be used. Because the process doesn't change, the drink mix and water can be fed into the mixer without stopping in order to produce sports drinks.

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takes place, and the materials are removed. This process can be repeated time after time or it can occur only once, and then a different process can take place. Batch operations are usually used when smaller quantities of finished products are desired for something like pharmaceuticals.

Chemical Plant Design

In all fields of engineering, the engineer is often the designer of processes. Engineers are asked to design a system or process that will increase the value of materials. Chemical engineering is no different.

Chemical engineers are often asked to design chemical facilities that take in raw materials, perform some sort of chemical process, and create products that are more valuable in the end. Chemical plants are designed to be profitable to the owner, safe for the workers, and friendly to the environment.

Plant layouts are designed based on the economics of construction and operation, the specific requirements of the processes that will take place, the convenience of the maintenance that will be necessary, the possibility of future expansion, and the safety of all the workers.

Block flow diagrams are extremely basic representations of major processes in a plant. See **Figure 15-18**. ***Process flow diagrams*** are similar, but they are much more detailed, showing main flow of chemicals, general processes, and main equipment. ***Piping and instrumentation diagrams*** show every detail of plant layout and design.

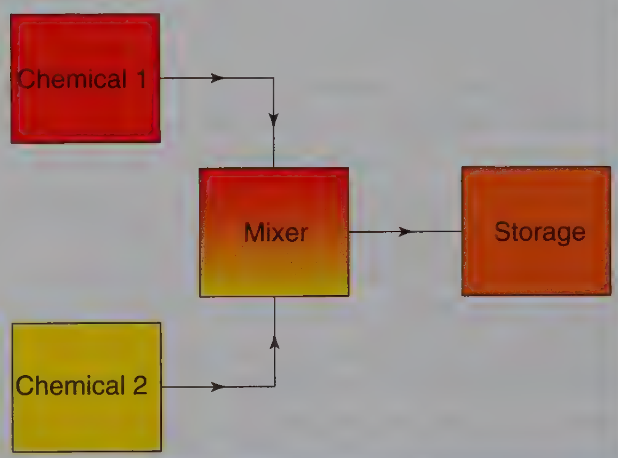

Figure 15-18.

This simple block diagram shows the overall processes in a plant without going into much detail.

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They include all chemical flows, instrumentation, temperature, control systems, location of all equipment, and everything else needed to build and maintain the facility. It is very important to create designs using these kinds of diagrams so the designs can be studied and communicated. Schematics, 3-D models, CAD line drawings, and 3-D computer models are also used in the design and communication phases.

Plant Location

There are many considerations to be made in the selection of a location for a new chemical plant. These considerations include the location of raw materials, energy resources, and local communities.

Plants should be located within reasonable proximity to raw materials if their transport is expensive. In the case of a petroleum refinery, locating the plant close to an adequate shipping terminal or existing pipeline would be cost effective because crude oil could then easily be transported to the facility. In the case of pharmaceuticals, where transport is less expensive, proximity to raw materials might be less important.

Many plants require energy sources like electricity, natural gas, coal, and oil. These plants should be located where these resources are readily available. Some plants require large amounts of water for things like cooling and a place to discharge this water after it is used. These plants might be best located near a body of water.

The local community should be considered as well. Some communities welcome a new plant because of the jobs it creates, the tax revenues it generates, and the general boost to the local economy. Other communities might actively oppose a new plant in their area. Local tax rates, building codes, environmental regulations, and the availability of workers should also be considered.

The property should be large enough to support the proposed facility, as well as any future expansion. The site should be reasonably flat with adequate drainage. The soil should be able to support the construction of the proposed facility.

Site Layout

Site layout is also an important consideration. Site layout describes the specific location of all required facilities, such as the plant itself, roads, parking, storm water management, and utilities.

The site should be laid out in the most economical way possible. It should allow for efficient flow of materials through the site. This includes the materials used in the chemical processes, energy products, utilities, vehicles, people, and maintenance.

Waste

Waste is a by-product of chemical operations. Waste is a major consideration in the chemical industry because of the cost of its disposal. Chemical engineers design chemical plants to minimize the amount of waste that is created and to treat and dispose of any waste that is created.

In the chemical industry, the first step in waste management is to not make the waste in the first place. All processes are examined to see when the waste stream can be minimized. Often, waste is the result of impure feed materials. For example, crude oil commonly contains nitrogen, salt, sulfur, and metals. If these impurities are not removed, they can lead to quality issues. If the crude is used to produce plastics, the plastics could be worth less money or simply be unusable. Improving the purity of the materials used in a reaction can minimize waste. Chemical processes often require the separation of one chemical from another, but this process rarely separates out 100% of the materials. Improving this process can minimize waste. Choosing fuels that burn more cleanly can also limit the waste that is generated.

Wastes can also be minimized through recycling. Careful examination can help engineers find a use for a material that is thought of as waste from an operation. It can sometimes be reused within the plant or sold to another company for their use.

All waste must be disposed of in a way that meets local regulations. Sometimes this requires treating the waste on site prior to its disposal. Toxins can be filtered out, separated by mechanical means, or chemically neutralized. Imagine a process that creates a mixture of oil and water. Water contaminated with oil cannot be disposed of into a public sewer or in any other way. The oil must first be separated out and safely disposed of. Then the water can go into the sewer.

Protection

The ***Occupational Safety and Health Administration (OSHA)*** is an agency of the US Department of Labor. OSHA's mission is to ensure safe and healthful working conditions for workers by authorizing enforcement of standards developed under the Occupational Safety and Health Act of 1970. OSHA inspects workplaces to ensure protective gear is worn by employees, guards are on all moving parts so workers remain safe, exposure to hazardous materials is limited, confined spaces are entered into safely, and more.

OSHA's ***"right to know" laws*** are designed to ensure people know what chemicals they are being exposed to and what the health effects could be.

Employees have a right to know what chemicals they are using at work. Community members who live near plants using hazardous chemicals have a right to know what chemicals they are exposed to. This information is provided through ***material safety data sheets (MSDS)*** and training. See **Figure 15-19**. All chemicals must have an MSDS that includes the chemical's common name and chemical name, hazard warnings, first aid for exposure, disposal information, transportation requirements, and the

ELMER'S

Material Safety Data Sheet

F

1. Chemical Product and Company Identification

```
DESCRIPTION:     ELMER'S GLUE-ALL
PRODUCT TYPE:    PVAC BASED ADHESIVE
APPLICATION:     FOR PRODUCT CODES SEE SECTION 16
```

- **Manufacturer/Supplier Information**

```
MSDS Prepared by:
Elmer's Products, Inc.                         Emergency Phone Number
1 Easton Oval                                  Poison Control Center
Columbus, OH  43219                            1-888-516-2502
For additional health, safety or regulatory information, call 1-888-435-6377.
Call 1-800-848-9400 to place an order or request additional MSDSs.
```

2. Composition, Information on Ingredients

No hazardous ingredients known to company.

3. Hazards Identification

3.1 Emergency Overview

```
Appearance                          Milky white liquid
Odor                                Mild acetic aroma
CAUTION!
Not a significant fire hazard.
May cause eye irritation
```

- **HMIS Rating**

Figure 15-19.

An MSDS for glue describes the product and application. It includes manufacturer information and any hazardous information workers should know.

Courtesy Elmer's Products, Inc.

manufacturer's name and address. Employers are required to inform employees about hazard communication requirements, where hazardous materials are located, the written hazard communications program, how to detect hazardous chemicals, protective measures for dealing with hazards, the hazards involved in work duties, and how to read and understand labels and MSDS.

Chemical Engineering in Action

Chemical engineers are quite often called on to solve major problems in our society, and these problems are frequently related to providing the energy we need without harming our environment.

Going Green

Bioplastics

Have you ever heard of the ***Garbage Patch*** in the central North Pacific Ocean? It is an area of marine trash estimated to be about twice the size of Texas and made up mostly of plastic. There is a ***gyre***, or rotating oceanic current, in the North Pacific Ocean. See **Figure A**. The currents flow around the outside, but not as much in the middle. The middle part has less movement, so trash has accumulated over the years. It is made up mostly of plastic because it can take hundreds of years for plastics to decompose compared to something like paper that might only take weeks.

Our highways, neighborhoods, and even our oceans are increasingly polluted with plastic trash that is not going away any time soon. So what is the answer?

The solution to another of our great societal problems could come from chemical engineers in the form of bioplastics. See **Figure B**. ***Bioplastics*** look, feel, and function much like traditional plastics that were made from petroleum products. However, bioplastics are made from renewable biomass sources such as cornstarch, pea starch, glucose, vegetable oil, potatoes, and cane sugar.

Because bioplastics are biodegradable, they are most popular for use in disposable products like clear film, plastic silverware, disposable plates, and disposable cups. But they have also been used for things like fuel lines and cell phone cases.

One problem with bioplastics is in their disposal. Bioplastics must be composted rather than recycled,

Figure A.

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Figure B.

Courtesy Metabolix, Inc.

so they have to be separated out of the plastic stream. New sensor technology is making this possible.

Bioplastics are still in their infancy. The hope is that technological and chemical advances will help bioplastics replace oil-based plastics, decreasing our dependence on oil, producing waste that can be composted, and providing a sustainable source of high-quality plastics.

More than half of the electricity in the United States is generated from the burning of coal. According to the US Department of Energy, the United States has enough coal resources to meet our current demand for another 250 years.

The problem is that burning coal emits so many pollutants that can lead to respiratory illness, cause acid rain, and contribute to greenhouse gasses. Chemical engineers may be able to solve this problem in the near future so coal can be used as a safe, environmentally friendly, clean, abundant energy source.

You have probably heard the term ***clean coal***, which refers to numerous techniques used to trap harmful gases like carbon dioxide (CO_2) and other toxins. Carbon dioxide capture and storage (CCS) involves removing the CO_2 either before or after the coal is burned and storing it deep in the ground.

One clean coal method is ***coal gasification***. Rather than burning coal directly, coal is broken down into its basic chemical parts using heat and pressure with steam. The parts can be easily separated, and CO_2 can be sequestered. Sulfur and ammonia can be removed and sold for profit. Solids are either removed during gasification or are filtered out downstream. Many solids can also be sold. The result is a synthetic gas that can be burned cleanly to produce electricity.

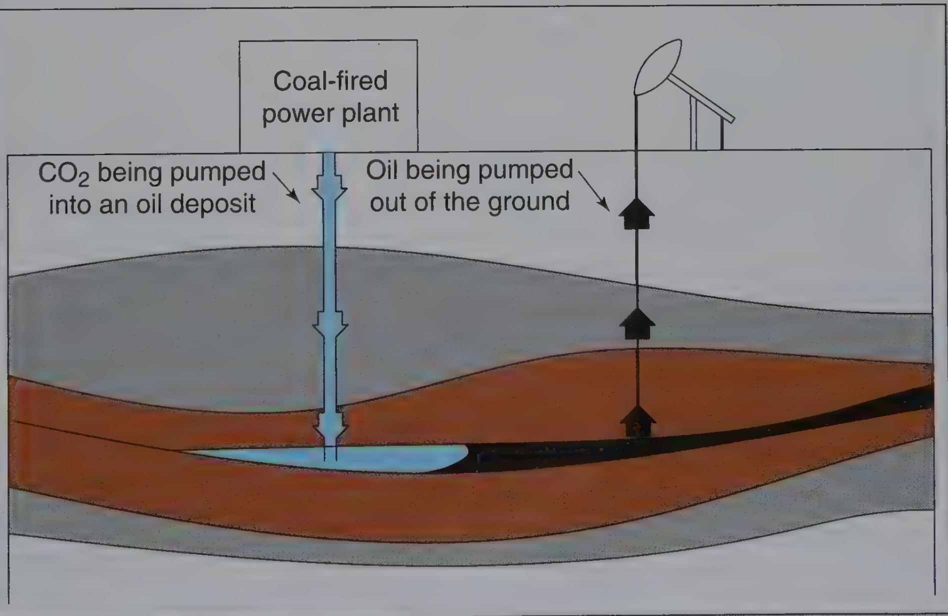
CO_2 can be separated out after coal is burned using traditional methods, but it is very difficult, more expensive, and less effective.

The most promising sites for storage are deep geological formations and depleted oil and gas reservoirs. This is currently expensive and there are concerns about the long-term storage of CO_2 and fears that it could escape. Engineers are working hard to reduce costs, increase the amount of carbon that can be trapped, and ensure long-term reliability of the carbon storage.

CO_2 is commonly pumped into natural gas and oil reservoirs to help push out the natural gas and oil. See **Figure 15-20**. This process is called enhanced recovery. The CO_2 stays in the reservoirs. This is a way to sequester CO_2 at low cost due to the oil and natural gas products that are recovered.

Chemical engineers have always been called on to solve our energy needs and to help ensure our energy usage has a minimal effect on our environment. Of course, our long-term energy goals should be to use truly clean and renewable energy sources like wind and solar. However, chemical engineers may be able to provide other relatively clean and economically viable solutions in the short term that meet our energy needs without harming our environment.

Figure 15-20.
Carbon dioxide can be pumped into a reservoir to push out oil or natural gas.



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Summary

- Chemical engineers use their extensive background in chemistry, thermodynamics, fluid dynamics, and industrial processes to design, build, monitor, and manage large-scale chemical facilities.
- The largest professional society for chemical engineers is the American Institute of Chemical Engineers (AIChE).
- Chemical engineers are different from chemists. However, chemical engineers must have a firm understanding of chemistry.
- Thermodynamics can be used to study the change of energy into work and heat. The main laws of thermodynamics are used to predict the operation of systems.
- Chemical reactions are examined using mass balance to ensure the same amount of materials going in equal the same amount of materials going out.
- Fluid dynamics is the study of liquids and gases in motion. Fluid dynamics is important to chemical engineers because so much of what they do deals with fluids flowing through pipes from one place to another.
- Throughout the design phase and the constant monitoring of chemical operations, it is crucial for chemical engineers to measure flow rate, pressure, and temperature.
- Chemical engineers often design chemical facilities that take in raw materials, perform some sort of chemical process, and create products that are more valuable.
- The Occupational Safety and Health Administration (OSHA) ensures safe and healthful working conditions. OSHA's "right to know" laws are provided through material safety data sheets (MSDS) to inform employees what chemicals they are using at work.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. What is *chemical engineering*?
2. Compare and contrast chemists and chemical engineers.
3. What level of education is required to become a chemical engineer?
4. _____ is the study of work, energy, and efficiency in large-scale systems.
5. Which law states that energy cannot be created or destroyed?
   A. Law of conservation of mass.
   B. Entropy law.
   C. Law of conservation of energy.
   D. Zeroth Law.
6. What is *entropy*?
7. Which law is an observation that deals with thermodynamic equilibrium?
   A. First law of thermodynamics.
   B. Second law of thermodynamics.
   C. Third law of thermodynamics.
   D. Zeroth Law.
8. What type of balance is taken at two different points to show what is happening between one point and another?
9. _____ is the thickness of a liquid.
   A. Viscosity
   B. Fluid flow
   C. Surface tension
   D. Laminar flow
10. According to Bernoulli's Principle, as flow increases, pressure _____.

11. A(n) _____ is used to measure fluid flow.
    A. liquid column gauge
    B. change-of-state measurement device
    C. mass flowmeter
    D. Bourdon-style gauge
12. Compare and contrast continuous and batch production of chemicals.
13. Why is waste a major consideration in the chemical industry?
14. What information is provided in a material safety data sheet for chemicals?
15. Describe coal gasification.

Reinforce *learning*

While studying this chapter, look for the online resources icon to:

- **Assess** your knowledge with self-check pretest and posttests.
- **Practice** vocabulary terms with e-flash cards and matching activities.
- **Expand** learning with interactive activities and animations.
- **Reinforce** what you learn by submitting end of chapter questions.

www.g-wlearning.com/technologyeducation/

Companion Website

Study on the go

Use a mobile device to access online study activities including: e-flash cards, animations, and self-check pretest, and posttest assessments.

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G-W Mobile

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Chapter 16

Engineering as a Profession

Check Your Engineering IQ

Before you read this chapter, assess your current understanding of the chapter content by taking the chapter pretest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess *knowledge*

Objectives

After studying this chapter, you should be able to:

- List and define the various functions of engineers.
- Describe the professional aspects of engineering.
- Describe the purpose of codes of ethics.
- Provide examples of the types of impacts of engineering.
- Describe the future of engineering.

Key Terms

Accreditation Board for Engineering and Technology (ABET)
codes of ethics
construction engineer
design engineer
development engineer
economic impact
environmental impact
ethics
green design
management engineer
negative impact
operations engineer
patent
positive impact
production engineer
Professional Engineer (P.E.)
research engineer
risk analysis
sales engineer
societal impact

Practice *vocabulary*

Engineering is a profession that reaches millions of people every day. Everyone who uses a cell phone, drives on a road, rides a bike, takes medication, or watches television is interacting with a product that has been designed, manufactured, or constructed by an engineer. These products, like all engineered products, are designed with several aspects in mind, including function, safety, and economics. Designing products that function well, are safe to use, and make a profit when sold requires a group of people with specialized skills. The skills of an engineer are gained through both education and experience. This chapter focuses on the various functions, the professional requirements, and the impacts of engineering.

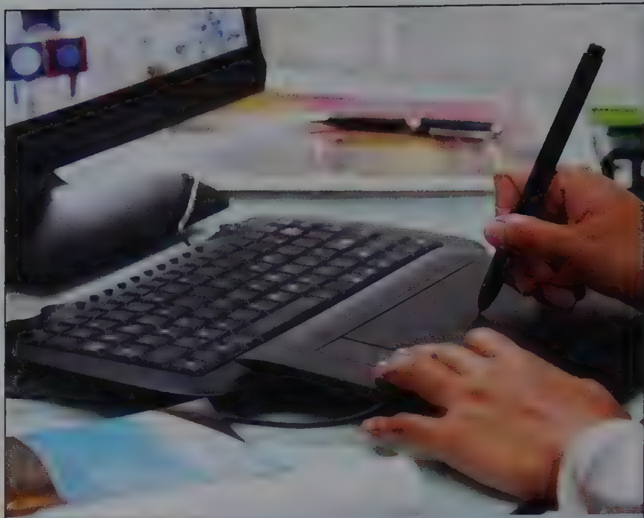

Figure 16-1.

Design engineers work on designs for new products.

OtnaYdur/Shutterstock.com

Functions of Engineers

When you think of the job of an engineer, you may first think of a designer creating new and innovative products. Design is certainly one function of an engineer. Engineers known as ***design engineers*** use an engineering design process to create a product that meets the needs of a client. See **Figure 16-1**. However, there are a number of other functions involved in engineering careers in all fields of engineering. Instead of design, engineers may focus on research, development, production, operations, sales, or management. ***Research engineers*** work with scientists to find uses of scientific discoveries. These engineers often work in government or university laboratories and focus on very specific materials and processes. See **Figure 16-2**. For example, a research engineer

Figure 16-2.

Research engineers are commonly found in research labs in corporations or universities.

RGtimeline/Shutterstock.com

in materials engineering may find new ways to grow carbon nanotubes for use in a nanotechnology environment. The successful outcomes from research engineers are often licensed to be sold or reported in academic journals so other engineers can use the new information or processes.

Development engineers are involved in the testing and analysis of ideas and products. In some situations, companies may employ predevelopment engineers to use computer modeling or even surveys to test out ideas before they go through the entire design process. In other cases, development engineers focus on testing and analyzing the products that are created by design engineers. Development engineers may also oversee the design process and the work of design engineers. Once products are designed and tested, production and construction engineers oversee the manufacturing and construction of the products. Both production and construction engineers determine the best methods to turn raw materials into the final products. ***Production engineers*** plan, coordinate, and schedule the manufacturing of consumer goods. ***Construction engineers*** complete the same tasks for structures such as roads, bridges, and skyscrapers. See **Figure 16-3**. ***Operations engineers*** control and maintain large systems, such as manufacturing facilities, railroad systems, and traffic systems.

Figure 16-3.
Construction engineers are responsible for reviewing designs for construction sites.

Marcin Balcerzak/Shutterstock.com

Other engineers work on the more business side of the profession. ***Sales engineers*** work with clients to find products that meet their needs. These engineers often present final products to clients and handle the financial aspects of engineering design. They must understand the way the products work. See **Figure 16-4**.

Figure 16-4.
Sales engineers must have an understanding of how a design works in order to present it to clients.

Konstantin Chagin/Shutterstock.com

Management engineers coordinate all of the engineering processes including materials and human resources. These engineers focus mainly on the policy, legal, and labor aspects of the engineering process. Lastly, a number of engineers enter the academic world and become engineering professors.

The role or function engineers choose is often based on their own strengths. An engineer who has strength in planning and coordination may choose the production or construction functions of engineering. An engineer who is very analytical and likes the laboratory environment may choose to work as a research engineer. All functions of engineers, however, require skills in creativity and problem solving.

Teamwork

Because engineers often have their own strengths and specialization areas, it is common for engineers to work in teams. This is especially true in large engineering projects. At many stages in the engineering process (from design to production), there is a need for engineers to work together. In some cases, it may be to have more people thinking about a potential solution or to use more people to brainstorm ideas. In other cases, it may be to make sure that all parts of the project are being considered. Because engineers often work in teams, it is important for all engineers to have good teamwork skills. Members must be able to communicate and get along in order to work together successfully.

Going Green

Making Green Decisions

Green design and green engineering stress the reduction of pollution and waste, the use of renewable resources, and the protection of people and environment. However, it is difficult for all technologies or engineered products to meet all of these specifications. Consider nuclear power, **Figure A**. Traditional power generation creates a large amount of greenhouse gas. Greenhouse gases are gases that trap heat in our atmosphere and could contribute to global warming. Nuclear power plants do not emit greenhouse gases. This is viewed by many as a major advantage of nuclear power, which in part meets some of the components of green design (protection of environment and reduction of pollution).

However, the generation of nuclear power does create waste. The waste that is created is spent nuclear fuel that will remain radioactive for thousands of years. One main concern of green engineering is the reuse and recycling of waste. Nuclear waste cannot currently be reused. Scientists and engineers are hopeful that in the future there will be a use for the spent nuclear fuel. Most of the waste is currently being stored in concrete facilities at the sites of the nuclear power plants. So, there are aspects of nuclear power that are not components of green design (creation of waste and protection of people).

Figure A.

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Nuclear power is a good example of the benefits and costs of engineered products and systems. It is also an interesting example because it has many features of green engineering, as it is sustainable and does not produce air pollution but does create waste that is not only unusable but also radioactive. The impacts of engineering and technological solutions are rarely clear-cut and usually contain both costs and benefits. Any use of a new or existing technology with the intention of it being a "green" technology must include a review of all its impacts and benefits.

Engineering Profession

A profession is a career field that meets several criteria. Common criteria for a profession include a specialized body of knowledge, the right to make professional judgments, a regulating body, and a code of ethics. Several careers that are considered professions include doctors, lawyers, teachers, and engineers. In the engineering profession, there is even a specific designation for a Professional Engineer, explained later in this chapter. Some of the elements of a profession have been discussed in previous chapters in terms of the education and associations that are specific to each field of engineering. This section provides an overview for all fields of engineering.

Professional Knowledge

The professional knowledge and the information needed to make professional judgments comes from the education and experience that is required of engineers. The first step to becoming an engineer or engineering technician is obtaining a college degree. An associate or bachelor's degree is usually required to become an engineering technologist or technician. Associate degrees are generally two-year degrees and bachelor's degrees are four-year degrees. An engineering technology degree focuses more on application and includes less mathematics and science courses than engineering degrees require.

A degree in engineering is a bachelor's degree, which requires either four or five years of study. Most bachelor's degrees in engineering are structured the same. The first two years of study are focused on math, science, and general studies courses, such as history or English composition. The math and science courses include several levels of physics, calculus, statistics, and introductory engineering courses. Students may not have to select an engineering discipline in the first two years of study. The final two (or three) years of study are focused on engineering courses that are specific to a discipline of engineering. These courses could include geomatics, structural analysis, and hydraulic engineering for a civil engineering student or pneumatics and mechanism design for a mechanical engineering student. Many engineering programs also require students to complete internships with engineering companies. An internship is a work experience in which a student works as an assistant in a company for several months under the guidance of a mentor.

The highest quality engineering programs are accredited by the ***Accreditation Board for Engineering and Technology (ABET)***. ABET requires students to graduate with a number of abilities that range from being able to apply their math, science, and engineering knowledge; conduct experiments and analyze results; identify and solve engineering problems; design systems and components; to working well on teams and understanding the impacts of engineered solutions. Dedication and hard work are required in order to graduate from an engineering school and achieve the abilities outlined by ABET. See **Figure 16-5**. It will require hours of work in laboratories and libraries.

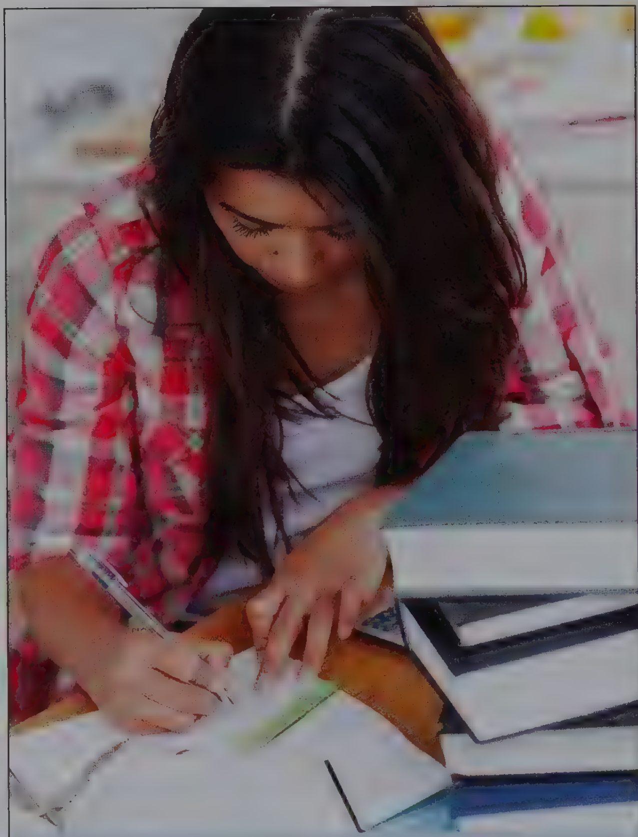

Figure 16-5.

In order to meet the requirements of ABET, students must work hard and study.

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Regulating Bodies and Societies

Education and gaining knowledge is just the first step to becoming an engineer. The work of many types of engineers is regulated by individual states. This is especially true of civil, mechanical, structural, and electrical engineers. All states require these engineers to become registered if they are going work directly with the public. For example, a structural engineer who wants to design and give final approval for buildings must be licensed in that state. Licensure requires an engineering degree, four years of professional experience, typically working under a Professional Engineer, and passing scores on two engineering exams administered by the National Council of Examiners for Engineering and Surveying. The first of the two exams, the Fundamentals of Engineering (FE) exam covers general engineering topics, such as statics and dynamics, material properties, and ethics. The second test is the Principles and Practice in Engineering (PE) exam. The PE exam is more specific to the engineer's chosen engineering discipline. There are nearly 20 discipline exams to choose from. An engineer that has completed the licensure requirements is known as a Professional Engineer. The title of ***Professional Engineer (P.E.)*** is an important designation because Professional Engineers are allowed to approve, sign, and stamp plans and documents. See **Figure 16-6**.

Figure 16-6.

The designation of Professional Engineer allows engineers to stamp their seals on designs, which means the designs have been approved by engineers.

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While the practice of engineering is regulated by states, each field of engineering also has societies and associations that promote the interests of their field. The organizations promote the interests of their fields by publishing journals and newsletters that include new and important findings for the field; by organizing conferences, meetings, and seminars for members to discuss new trends in the field; and by publishing codes, standards, and policies for the profession. Engineering associations include broad societies such as the American Society of Civil Engineers (ASCE), the Institute of Electrical and Electronics Engineers (IEEE), and the American Society of Mechanical Engineers (ASME). These organizations attempt to serve the needs of the entire field. More specialized organizations, such as the International Association for Bridge and Structural Engineers (IABSE) and the National Association of Power Engineers (N.A.P.E.), also exist for engineers who specialize in those fields.

Some of the larger societies represent over 100,000 members. While most societies are focused on specific engineering disciplines, some organizations focus on engineers from various disciplines. The National Society of Professional Engineers (NSPE) is the professional organization for engineers (mainly those who have become Professional Engineers) from any area of engineering.

Ethics

We are faced with many decisions throughout our daily lives. Some decisions, like which homework to complete first, are fairly minor. However, some are much larger and have bigger implications. For example, a much larger decision would be if you choose not to complete any of your homework and then consider cheating off of a friend's homework. This type of decision is

an ethical decision. ***Ethics*** are guidelines that we use to help us make decisions about our behavior. Ethic decisions often involve virtues such as honesty, justice, fairness, and truthfulness. The previous example was an ethical decision made in our personal lives.

Professionals, such as engineers also face ethical decisions. Most professions have developed codes of conduct or codes of ethics to help professionals make ethical decisions. There are several codes of ethics in engineering that have been developed by engineering organizations and societies. See **Figure 16-7**. ***Codes of ethics*** in engineering are sets of guidelines that should be followed when engineers interact with the public, their employers, their clients, and other engineers. If codes of ethics are followed, it helps not only the individual engineers but also helps maintain the public's trust in the profession.

In engineering, like most professions, codes of ethics are important because engineers have specialized knowledge that the general public does not. Their knowledge, if used in unethical ways, could be harmful to the public. For example, it would be unethical and harmful for an engineer to create a new product knowing it is unsafe while telling the public that it is safe. Knowingly deceiving the public is unethical. In engineering codes of ethics, the first priority of engineers is to maintain the safety of the public. Aspects of engineering design such as cost, time frame, and appearance are all less important than safety. Engineers know they cannot make decisions to reduce costs if it makes the product unsafe.

Other ethical principles include being honest and forthcoming. An example of this is being honest about a flaw in a product that the engineer designed. An engineer may find a problem in a product after it has been manufactured. It is that engineer's ethical duty to report the design flaw, even if it means an added cost to the company. This is often the case when products are recalled.

Another aspect of engineering ethics has to do with competence and expertise. It is unethical for engineers to complete projects for which they are not qualified. For example, civil engineers are

NSPE Code of Ethics

Preamble

Engineering is an important and learned profession. As members of this profession, engineers are expected to exhibit the highest standards of honesty and integrity. Engineering has a direct and vital impact on the quality of life for all people. Accordingly, the services provided by engineers require honesty, impartiality, fairness, and equity, and must be dedicated to the protection of the public health, safety, and welfare. Engineers must perform under a standard of professional behavior that requires adherence to the highest principles of ethical conduct.

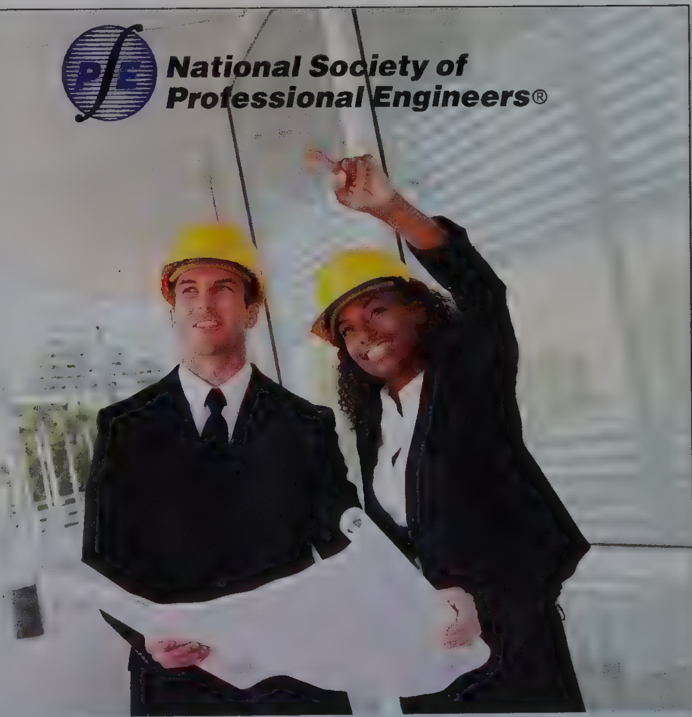

Figure 16-7.

Codes of ethics have been developed by several organizations. The preamble for the NSPE Code of Ethics summarizes the important points of their code.

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not qualified to design a computer circuit board because it is outside of their expertise. It is also unethical to claim you have expertise in an area in which you have not been trained.

The protection of the public is the main priority in engineering ethics, but it is not the only aspect. Other aspects of engineering ethics cover the business side of the job. This includes ethical ways to bid and to be awarded projects. It is common for engineers to write bids for engineering projects. The bid includes the scope of the project and estimated costs and timelines. It would be unethical of an engineer to submit a low bid knowing it would cost more to complete the project, or if the engineer knew unsafe materials or practices would have to be used to complete the project at that cost.

These and other ethical principles and rules help engineers focus on protecting the public. It also helps engineers remain honest and maintain the public respect for their profession.

Engineering Impacts

The impacts of engineering can be seen in nearly all aspects of our lives. Think of computers, for example. Computers have influenced and changed our society, our financial systems, and our environment. It is hard to think of aspects of our lives that have not been touched by computers. But have all of the changes and impacts been positive? Engineering has the power to change many aspects of our lives, but it must be done with both the positive and the potential negative impacts in mind.

Areas of Impacts

Engineered products can have far-reaching impacts. Think of how electricity, roads, and air travel have changed the world. Engineering and engineered products can have personal, societal, economic, and environmental impacts.

Personal impacts affect individual lives. Engineered products, such as vehicles, communication devices, and medications, have personal impacts. However, most products are engineered to have larger impacts and to serve more than individuals.

Societal impacts are the effects that engineered products have on the lives of groups of people. These include impacts in areas such as housing, safety, food, communication, and transportation. Water purification, for example, is a result of engineering that can have a large societal impact. See **Figure 16-8**. Imagine the difference access to clean water makes to a community. Think of the societal impacts that have been made by computers and public accessibility of the Internet. Today, there is not much thought given to the vast amount of information that is accessible to us through computers, handheld devices, and television. This kind of information access has changed and will continue to change society. It may even change the educational system. For example, is it important to learn all the state capitals when that information is so easily accessible?

Figure 16-8.

Engineered solutions to a problem, such as access to clean water, could have a large impact on people around the world.

Asianet-Pakistan/Shutterstock.com

Is learning in a classroom the best way to learn, or would it be better for students to learn in online environments? See **Figure 16-9**. These types of questions will be asked, and the answers will have a large impact on society, due to the work of engineers.

The work of engineers also has large economic impacts. ***Economic impacts*** are the effects products have on financial systems. The most immediate economic impact is the profit that is made from an engineering project. Engineers and engineering companies operate like any other company, as their goal is to make a profit from their work. They often make income from their designs and the products they produce. Engineers work to protect their ideas and products so that others cannot profit from them. Obtaining a patent helps to protect their ideas, designs, and products from others. A ***patent*** is an exclusive right that is granted by a government to the creator of a new product or design so others cannot produce it without permission. To obtain a patent in the United States, an inventor of a new product must file an application with the US Patent and Trademark Office. Within the application, the inventor must describe and provide drawings of the product and sign an oath that states the inventor believes he or she is the first to invent this product. The patent office then reviews the application and determines if the invention should receive a patent. Once the patent application has been filed, the inventor can state the invention is *patent pending*.

Another economic impact of engineering is the creation of jobs. It takes a large amount of people with a range of skills to build skyscrapers, interstate systems, chemical plants, and vehicles. Economic impacts can also be much larger. Consider the economic impacts of nearly any transportation system. A highway system, for example, is an engineered system that may link thousands of towns and cities together across the nation. Traveling across the highway system creates demands for products and services. Travelers will need vehicles and places to refuel, eat, and sleep. All of these products will be available for purchase, and most require the work of various engineers.

Another impact of engineering is on the environment. ***Environmental impacts*** are effects engineered products have on human health and the world around us. Concerns regarding the environmental impacts of engineering are currently high.

Figure 16-9.
The way students learn can be impacted by advances in educational technology.

Rob Marmion/Shutterstock.com

Movements like green design and the growing of organic foods stress sustainability and positive environmental impacts. ***Green design***, or sustainable design, focuses on creating products that are not harmful to environment throughout their life cycle. That includes materials, manufacturing practices, and disposal of the product. Environmental impacts include air, water, and soil pollution, as well as such issues as land use. See **Figure 16-10**.

For example, building a dam has a large impact on the land and resources around the dam. Dams are engineered products that control the flow of water to be used for agricultural uses or the creation of electricity. When a dam is built, the flow of water is restricted, and a large lake or reservoir is created behind the dam. During the planning and construction process for building dams, entire towns have been relocated because they were flooded out when the dam was completed. Unfortunately, environmental impacts are not always known when a product is going through the design process.

Types of Impacts

The impacts of engineering are often viewed as positive. If you were to review the National Academy of Engineering's list of the 20 Greatest Achievements in Engineering, you would probably think of the good work that engineers have completed. See **Figure 16-11**. Electricity, the automobile, radio and television, highways, computers and the Internet, and health technologies have had positive impacts. However, not all of the impacts of these engineered products and their related technologies have been positive. The positive impacts can be viewed as benefits, and the negative impacts can be labeled as costs. The positive and negative impacts can either be intended or unintended. The unintended impacts are often unknown to the engineers during the design process.

Positive Impacts (Benefits)

The ***positive impacts***, or benefits, are the successful solutions to engineering design problems. The intended positive impacts are the

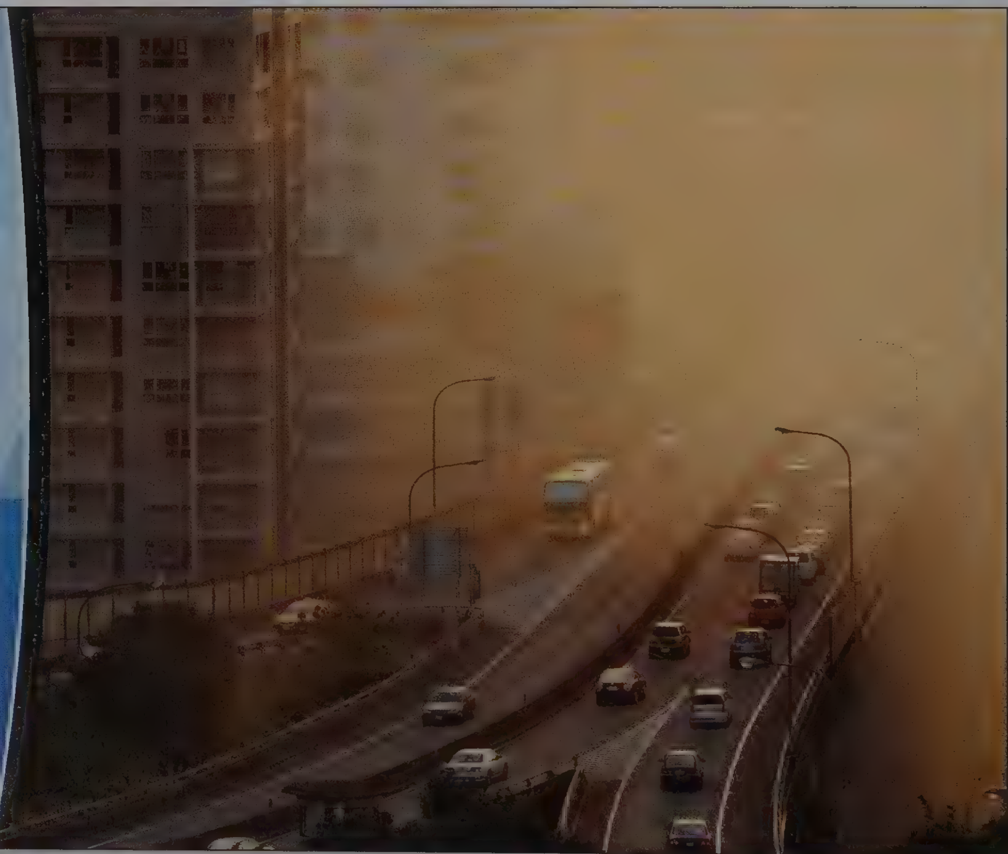

Figure 16-10.
Air pollution is a major environmental impact of some engineered products.

elwynn/Shutterstock.com

List of 20 Greatest Achievements in Engineering

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-Performance Materials

Figure 16-11.

The list of the 20 greatest achievements in engineering includes several designs and products we use every day because of their positive impacts.

National Academy of Engineering

benefit the engineer was hoping for or expecting. A new prosthetic hand that has more realistic function is an example of an intended positive impact because it was what the engineer was attempting to create. An aerospace engineer who designs a new wing shape that reduces fuel use by 10% and provides the same amount of lift has reached the positive intended outcome. The chemist and chemical engineer who have designed and produced a medication that cures the intended sickness have reached the positive intended impact.

However, there are often positive impacts that come from engineered products that are unexpected. Unintended benefits are usually welcomed by engineers because the engineered product is of greater use or benefit than expected. It may also lead to additional profit because the product may be marketed for additional uses. Sometimes, medications that are meant to solve one medical issue may be found to help other conditions as well. Aspirin, for example, was initially used as a pain reliever, but today, it is also used as a preventative treatment for heart attacks. See **Figure 16-12**.

Negative Impacts (Costs)

Negative impacts, or costs, are those effects that cause damage to people or the environment. Most negative impacts are unforeseen, or unintended. This is often because the engineers do not have a full understanding of how the product will be used or how it will evolve. For example, an unforeseen cost of computers has been social isolation (such as in office cubicles). When engineers were designing the first computers, some engineers believed that there would only be a market for a handful of computers in the entire world. See **Figure 16-13**. They had no way of predicting the negative impacts, because computers evolved into something more than they expected.

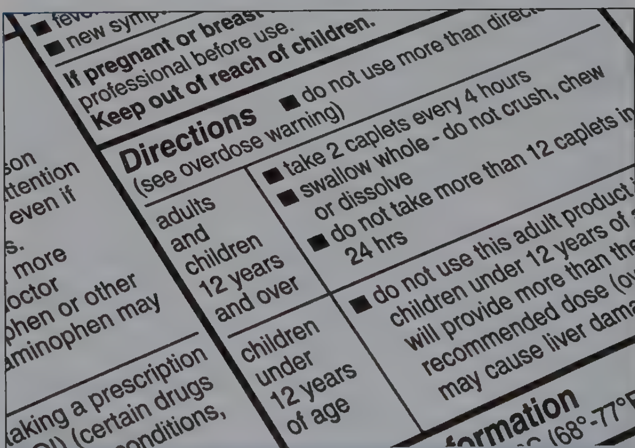

Figure 16-12.

Aspirin is an example of an engineered product with positive intended and unintended impacts.

Stephen VanHorn/Shutterstock.com

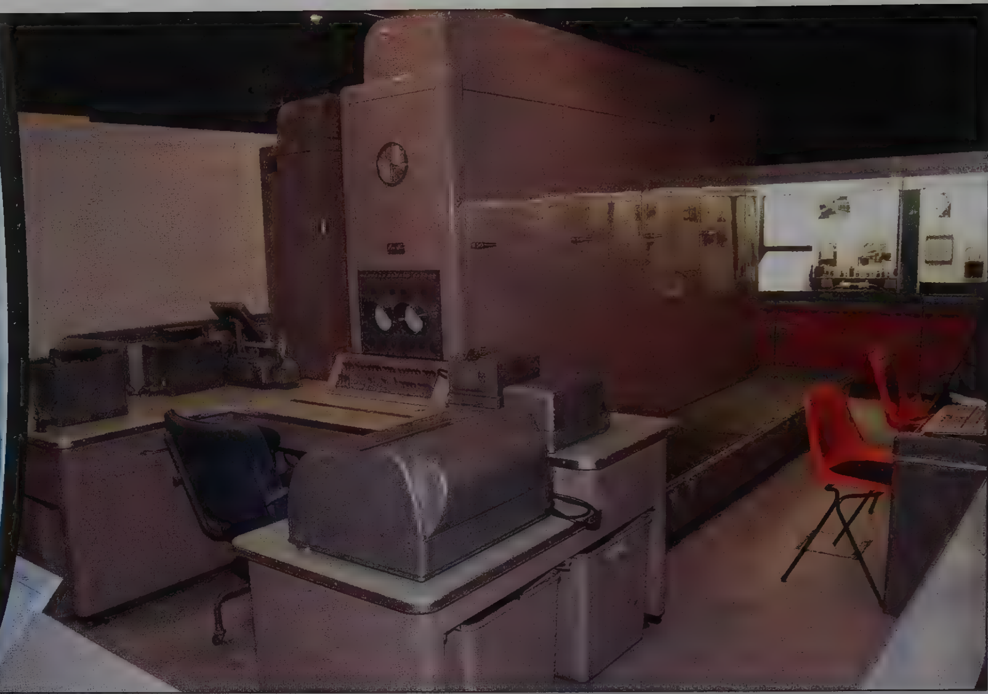

Figure 16-13.
Early computers were large machines that had very limited computing power compared to processors used in home computers today.

Tim Jenner/Shutterstock.com

Sometimes, the unintended costs are related to chemicals and materials that are harmful to the environment. See **Figure 16-14**. In many of these cases, the harmful nature of the chemicals was unknown at the time. This is the case for chlorofluorocarbons (CFCs), which contain chlorine, fluorine, and carbon atoms. CFCs were used as refrigerants and in aerosol cans. They were believed to be generally safe in most applications. However, they were later found to be linked to the depletion of the ozone layer once the CFCs were released into the atmosphere.

Figure 16-14.
The negative impacts created by some materials, such as plastics, are unintended impacts.

guentermanaus/Shutterstock.com

Some engineers and scientists worry about the potential unforeseen costs of the work engineers are doing in nanotechnology and genetic engineering. For example, one negative impact of genetic engineers is that it removes the diversity within plants. It may be possible to use genetic engineering to alter the genes of a corn plant so it produces larger ears of corn. However, all of the genetically engineered corn in the field will be exactly the same, meaning that if there were a fungus that damaged one plant, it could also damage all of the plants in the field, which would lead to huge crop losses.

You may be surprised to learn that some negative impacts are foreseen by engineers. Engineers who design automobiles, for example, know that there are negative impacts, such as air pollution and the potential for traffic accidents. They attempt to minimize the negative impacts as much as possible. In the case of the automobile, they may minimize the potential negative impacts by designing a low-emissions vehicle that is safer for the environment than other vehicles.

Risk Analysis

There are positive and negative impacts from all products and systems designed by engineers. Engineers attempt to uncover as many of the potential impacts as possible by conducting a risk analysis. A ***risk analysis*** is a process that identifies and evaluates as many of the potential impacts of an engineered solution as possible. Many states and communities require a risk analysis to be completed on civil engineering projects such as highways, subdivisions, and large industrial facilities. In a large engineering project, there may be a number of engineers from different departments that meet to conduct the risk analysis. This group would meet near the beginning and throughout the engineering process to reevaluate the risk that is involved in the project. This process is a more detailed version of listing the pros and cons of an idea.

The result of a risk analysis can lead to ethical decisions that must be made. In a highway design, the decision may be between the benefit of increased commerce at the cost of using farmland and having to relocate people's homes. These decisions can be very difficult to make and can force engineers to revisit their codes of ethics. Their goal is to at least balance the benefits with the costs in relation to society, economics, and the environment.

Future of Engineering

The future in general is difficult to predict, but there are certainly themes that will be present in the future work of engineers. Sustainability, renewable and clean energy, equitable access to resources and technology, and the advancement of health-related technology will all be important aspects of the future work of engineers. See **Figure 16-15**. However, there will also be problems engineers will face in the future that are currently unknown to us. For example, cyberterrorism and Internet security are computer and software engineering concerns that were not present even 20 years ago.

All of these issues are global issues. The work of engineers has become global, meaning the impacts of engineering projects are no longer confined to one community or even one nation. The profession of engineering is also becoming a global occupation. Engineering is a growing occupation in the United States, as well as in other countries, such as India and China. Future engineers will be given engineering problems that will help expand technology and influence human lives. These future problems, like today's problems, will have a range of benefits and costs that engineers will weigh as they develop solutions that will change lives in numerous ways.

Figure 16-15.
Advancements in medical technology, such as those in magnetic resonance imaging, will certainly be impacted by the work of engineers.

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Summary

- The work of an engineer can encompass many different roles in a range of fields. Some engineers are involved in design and development while others are in production and still others are in management or sales.
- The highest quality engineering programs are accredited by the Accreditation Board for Engineering and Technology (ABET). ABET requires students to graduate with a number of abilities.
- All engineers are regulated and follow a code of ethics. Engineers have specialized knowledge that the general public does not. Their knowledge, if used in unethical ways, could be harmful to the public.
- Engineer solutions have impacts in different areas, such as society and the environment. These impacts may be positive or negative and be intended or unintended.
- The work of engineers has become global, meaning the impacts of engineering projects are no longer confined to one community or even one nation.
- Future problems, like today's problems, will have a range of benefits and costs that engineers will weigh as they develop solutions that will change lives in numerous ways.

Check Your Engineering IQ

Now that you have finished this chapter, see what you learned by taking the chapter posttest. The test can be accessed on the mobile site by using a smartphone or on the G-W Learning companion website.

Assess knowledge

Test Your Knowledge

Answer the following questions using the information provided in this chapter.

1. *True or False?* Engineers focus on designing new products before focusing on different functions.
2. *True or False?* Engineering degree programs and engineering technology degree programs have different requirements.
3. *True or False?* When students graduate from an engineering school, they are granted the term Professional Engineer.
4. List two functions of a professional organization or association.
5. Define *codes of ethics*.
6. List an example of a societal impact.
7. The exclusive right given to an inventor so other people don't produce the invention is known as a(n) _____.
8. Define *green design*.
9. *True or False?* The positive impacts of an engineered product are always intended.
10. A process that attempts to identify as many impacts as possible is known as a(n) _____.
11. *True or False?* Engineering is a profession that is limited to the United States.

Matching: Match each engineering function with its description.

12. Development engineer
13. Production engineer
14. Operations engineer
15. Sales engineer

A. Plans and coordinates the manufacturing of a product
B. Controls a large system, such as a traffic system
C. Presents final products to clients
D. Tests and analyzes new ideas and products

Reinforce *learning*

Glossary

A

absolute pressure: The pressure relative to a vacuum. (15)

abutments: The structural components that connect the bridge to the ground at the ends of the bridge. (9)

Accreditation Board for Engineering and Technology (ABET): The organization that accredits high-quality engineering programs. (16)

actuator: A device used to convert fluid power into either linear or rotary motion. (10)

adhesion: The bonding of two materials using an adhesive material like glue or cement. (14)

aerodynamics: The study of how air flows around solid objects. (13)

aeronautics: The study of manned and unmanned craft within the earth's atmosphere. (13)

aerospace engineering: The design, construction, analysis, and troubleshooting of components in aircraft, spacecraft, missiles, and high-altitude vehicles. (1, 13)

aesthetics: The quality of being visually appealing. (6)

agricultural engineering: A branch of biological engineering focused on crop and livestock production. (11)

aileron: The component of a wing that is located on the outside rear of each wing and is adjusted for turning. (13)

air compressor: A device used by pneumatic systems to produce compressed gas. (10)

algorithm: A step-by-step procedure for solving problems or completing tasks. (12)

alloy: A mixture of a metal with one or more additional elements. Often a combination of two or more metals. (7, 14)

alternating current (ac): The current flow where polarity is constantly changing. (8)

American Institute of Chemical Engineers (AIChE): The largest professional society for chemical engineers, with nearly 40,000 members in more than 93 countries. (15)

American Wire Gauge (AWG): A system for sizing round wires based on their cross-sectional area where smaller numbers represent larger wire. (8)

ammeter: A meter that is used to measure current. (8)

anaerobic digestion: A biochemical conversion process that uses microorganisms to degrade biological material in an environment without oxygen. (11)

AND gate: A gate that provides an output of 1 only if both inputs (A and B) are 1. (12)

aneroid gauge: A type of gauge that uses a small bellows (like an accordion) that changes shape as pressure changes. (15)

angle of attack: The angle of the chord line of the wing relative to the airflow. (13)

angle of incidence: The angle of the wing in relation to the airplane body. (13)

arch bridge: A type of bridge that relies on the strength and rigidity of the arch. The strength of an arch is that the structural members are always in compression and that it can distribute the load throughout the arch to the abutments. (9)

artificial selection: The intentional selection of specific traits from animals or plants to make more prominent through breeding with similar animals. (11)

assembly drawing: A type of working drawing that shows how different parts fit together to create the entire object. (5)

assumption: An idea that is believed to be true and used in engineering design. (6)

astronautics: The study of manned and unmanned craft outside the earth's atmosphere. (13)

atom: A microscopic building block of matter, made up of electrons, protons, and neutrons. (8)

autonomous robot: An advanced robot that is programmed to respond to the world around it. (12)

B

batch chemical plant operations: A type of operation where chemicals are fed into the system, the chemical process takes place, and the materials are removed. (15)

battery: An electrical connection of two or more cells. (8)

beam: The structural member that carries horizontal loads. (9)

beam bridge: The simplest type of bridge used to span the shortest distance. (9)

bearing: A metal piece that is used to reduce friction with shafts by using smooth metal balls inside circular pieces of metal that fit around the shaft. (10)

belt: A band of material that is used to link and transmit energy between pulleys. (10)

bending: A force that causes a structure to sag when placed in the middle of it. (9)

Bernoulli theory of lift: The theory that states the airfoils being more curved on the top, so air traveling over the wing has to travel farther than the air traveling under the wing, causes the air flowing over the wing to flow faster relative to the wing than the air flowing under the wing, causing a low pressure zone above the wing and, therefore, lift. (13)

bimetallic temperature measurement device: A device that relies on the concept that different metals expand and contract due to temperature at different rates. (15)

binary code: The system of representing information in only 1s and 0s. (12)

biochemical conversion: A method of bioconversion that uses enzymes and other microorganisms to convert biomass materials into energy sources. (11)

bioengineering: A field that uses biological organisms and tools to help humans and other species live. (1, 11)

biomass: Biological materials that are used as a source of energy to produce heat or electricity. (11)

biomaterial: A substance that interacts with living systems. (7)

bioplastic: A type of material that looks, feels, and functions much like traditional plastics that were made from petroleum products. Bioplastics are made from renewable biomass sources, such as corn starch, pea starch, glucose, vegetable oil, potatoes, and cane sugar. (15)

biotechnology: The use of tools and resources to manipulate or model living organisms to meet human needs and wants. (11)

block flow diagram: An extremely basic representation of major processes in a plant. (15)

Bourdon-style pressure gauge: A type of gauge that uses coils of tubing. The shape of the coil changes in relation to the pressure changes. The coil is connected to the needle through a mechanical linkage. As the pressure changes, the needle moves. (15)

brace: A structural member used to provide structural stability. (9)

brainstorming: A technique for ideation that involves generating ideas in order to develop solutions. (2)

brainstorming web: A method of linking different ideas together by finding commonalities between them. (3)

buckyball: A carbon sphere made up of a series of hexagons and pentagons, similar to a miniature soccer ball. (7)

C

cantilever bridge: A type of beam bridge that can span greater distances than a simple beam bridge and often includes trusses in the framework. (9)

capacitor: A component that consists of two conductive plats separated by an insulator called a dielectric. Capacitors can store an electrical charge on their plates. (8)

casting and molding: The process of changing materials to a liquid or plastic state and then shaping them in or around a mold. (14)

cell: A device that generates electricity through chemical action. In biology, it is the structural and functional units of all living things. (8, 11)

cell biology: The study of cell structures. (11)

central core: A reinforced concrete shaft at the center of the building. (9)

ceramic: A very hard, inorganic, refractory, nonmetallic material with little electrical conductivity. (7, 14)

change-of-state temperature measurement device: A device that permanently changes colors when it reaches a certain temperature. (15)

chemical engineering: The branch of engineering that deals with the research, development, and design involved in the large-scale production of chemical products. (1, 15)

chemistry: The scientific study of materials, their properties, their interactions, and the changes that they undergo. (15)

circuit board: Commonly known as a PCB (printed circuit board). A rigid piece of insulation (typically fiberglass) is used as a platform for circuitry. Thin copper tracks are laid on the fiberglass and electronic components are soldered to the track. (8)

civil engineering: The engineering of both the structures that we build and the use and control of natural resources, especially water; the design and construction of public works projects or other large construction projects. (1, 9)

clean coal: A term that refers to numerous techniques used to trap harmful gases like carbon dioxide and other toxins, which usually result from the burning of coal before the escape into the atmosphere. (15)

cloning: The use of genetic engineering to create an exact copy of a living organism. (11)

coal gasification: A clean coal method where the coal is broken down into its basic chemical parts using heat and pressure with steam. The parts can be easily separated and CO_2 can be sequestered. Sulfur and ammonia can be removed and sold for profit. Solids are either removed during gasification or are filtered out downstream. Many solids can also be sold. The result is a synthetic gas that can be burned cleanly to produce electricity. (15)

codes of ethics: Sets of guidelines that should be followed when engineers interact with the public, their employers, their clients, and other engineers. (16)

cohesion: The joining of two materials through heat or pressure. (14)

column: A vertical structural member that transmits the load from above to other structural elements. (9)

combining: The process of joining parts through mechanical assembly and bonding. (14)

combustion: The thermochemical conversion process that involves burning of wood, municipal waste, or other biomass to create heat for humans, or to provide steam to power electrical generators. (11)

common constraints: The conditions that are in all engineering design problems. (3)

compact florescent lamp (CFL): A lamp that works on the same principle as the fluorescent lamp but designed to fit into normal light sockets. (8)

composite: A material that combines two or more materials. (7)

compost: A solid material used to fertilize agricultural crops and other plant life. (11)

composting: A biochemical conversion process that involves creating piles of biomass and allowing the natural organisms to break down the biological composition of the material. (11)

compression: A crushing force down the axis of a material that shortens the material. (9)

compression strength: The ability of a material to withstand a load that compresses or squeezes the material. (7)

computational fluid dynamics (CFD): A type of software that focuses on the use of fluids (air) in relationship to the flight of airplanes. Aerospace engineers can create computational models before they produce solutions to flight-based challenges. (6)

computer-aided drafting (CAD): The software used to create 3-D drawings of design solutions. (2)

computer-aided manufacturing (CAM) software: The software used to import CAD drawings while allowing users to input the type of material to be cut, the type and size of the cutter, the speed the cutter will move, and more. (12)

computer-aided process planning (CAPP): The use of a computer in order to design the processes that are used to manufacture parts. (12)

computer architecture: The way in which computers are designed, with a focus on the central processing unit (CPU), and how it works internally and accesses memory. (12)

computer engineering: The design, development, and testing of various aspects of computer systems; a unique field that overlaps electrical engineering and software engineering. (1, 12)

computer-integrated manufacturing (CIM): The manufacturing process in which computers control the entire production process. (12)

computer modeling: A type of modeling that uses computer software to create useful models for engineers. (6)

computer numerical control (CNC): Equipment used to convert CAD models into 3-D shapes. (2)

computer simulation: A type of simulation used for testing because it takes relatively little time and money to set up and run, but much can be learned. (2)

conductivity: The measurement of how well electricity flows through a material. (7)

conductor: A material with low resistance that easily passes electrons from one atom to another. (8)

constraints: The limitations of the design, such as materials, cost, size, and time. (1)

construction engineer: An engineer who plans, coordinates, and schedules for structures such as roads, bridges, and skyscrapers. (16)

continuity tester: A tool used to test if there is a complete path between two points. (8)

continuous chemical plant operations: A type of operation in which materials are fed into the facility, reactions occur, and materials are fed out of the facility constantly. (15)

continuous manufacturing: The type of manufacturing process that produces the highest number of products at the highest quality and the lowest cost because plants are designed to produce a specific product. (14)

corrosion: A reaction between a material and the environment that leads to deterioration of the material. (7)

cost control: The system of ensuring the company is profitable by controlling the resources used in the manufacture of products, including materials, machine time, and labor. (14)

cost feasibility: An evaluation of the effectiveness of the potential solution from a financial perspective. (4)

coulombs: The measure of the amount of electricity. One coulomb is equal to 6,240,000,000,000,000,000 (6.24×10^{18}) electrons. (8)

criteria: The guidelines to follow in order to successfully solve the problem. (3)

crop yield: The farmer's production per acre. (11)

current: The measure of electrons per unit time. (8)

custom manufacturing: The type of manufacturing process that is used to produce a single product or a small number of products, usually to meet a customer's particular need. (14)

cylinder: A device that uses the pressure of fluid to move a piston that is connected to a rod. (10)

D

database: A structured system of storing data in a computer system. (12)

design brief: The document that guides the design process and includes constraints, such as size, cost, and quality. (2)

design engineer: An engineer who uses an engineering design process to create a product that meets the needs of a client. (16)

destructive material test: A test that destroys a material or somehow makes a material unusable. (7)

detail drawing: A type of working drawing that shows the exact shape and size of an object and includes specific dimensions. (2, 5)

development engineer: An engineer who is involved in the testing and analysis of ideas and products. (16)

differential balance: A type of balance that is taken at the same point over time. (15)

differential pressure flowmeter: A type of flowmeter that constricts the flow by placing some sort of obstruction inside of a pipe or by narrowing the pipe at a point. As the fluid goes around the obstruction or through the narrow point, it speeds up and its pressure decreases. Flow rate is determined using the pressure at the obstruction or narrow point and away from that point. (15)

digital signal processing: The processing of signals that are represented by 1s and 0s. (12)

dihedral angle: The upward angle of wings away from the body that creates stability. (13)

dimensioning: A process used to describe the size of an object as well as the location of different features of a design. (5)

diode: A component that limits current flow to one direction. Can be used as rectifiers to change ac to pulsating dc. (8)

direct current (dc): Current flow in one direction, where polarity never changes. (8)

discussion forum: An area on the Internet where a person can type a question or comment and other people can answer the question or comment on the original message. (4)

DNA fingerprinting: A method used by forensic scientists to identify humans by their genetic makeup. (11)

drag: The force created by the friction of moving air that opposes propulsion. (13)

drilling: The act of cutting a circular hole down into the earth to extract things like water, natural gas, oil, and other materials from under the earth's surface. (14)

dynamic load: A sudden impact on the structure. (9)

dynamics: The study of forces that cause motion on physical objects. (9)

E

economic impact: The effect on financial systems, such as the profit that is made for an engineering project. (16)

elasticity: The ability to return to the original dimensions if the stress is removed. (7)

electrical engineering: The design and construction of electrical and electronic components and devices. (1, 8)

electricity: The movement of electrons. (8)

electrode: A solid conductor through which electricity enters or leaves a medium. (8)

electron: A negatively charged subatomic particle. (8)

electronic distance meter (EDM): A part of the total station, emitting infrared light. (9)

elevator: A control surface located on the rear of the horizontal stabilizer that controls vertical movement of the nose. (13)

end-of-arm tooling: The ability for a variety of tools to be attached to the end of a robotic arm. Examples include paint spray guns, welders, and grippers. (12)

energy: The ability to do work. (10)

engineer: A highly trained professional who uses both knowledge and skills to solve problems. (1)

engineering: The use of mathematics, science, and technology to create products and systems that improve the world. (1)

engineering design: The creative application of technology to design a system, product, or process to solve a given problem or meet a given need. (2)

engineering design process: A specific set of steps that lead the engineer from a problem statement to a final solution. (1)

engineering drawing: A drawing created to communicate products that will be manufactured. (5)

engineering economics: All of the financial considerations and decisions made during the production of a new design. (6)

engineering technician: The people who carry out technical work of engineers by using more technology and less scientific and mathematical knowledge. (1)

entropy: The tendency of all energy and matter to seek a state of uniformity. (15)

environmental impact: The effect engineered products have on human health and the world around us. (16)

environmentally conscious manufacturing (ECM): A process concerned with the entire life of a product from the time the raw materials are gathered to the time the product's life is over and it is disposed of. ECM tries to minimize scrap, reduce or eliminate hazardous waste, and makes the most effective use of natural resources. (14)

equilibrium: The state at which structures can oppose external forces and can transfer the load throughout the structure. (9)

ethics: The guidelines that we use to help us make decisions about our behavior. (16)

evolutionary biology: The study of how organisms and species evolve from different organisms. (11)

experimental research: A type of research that uses tests to discover information about a potential solution. (4)

F

facility engineering: The design of production facilities specifically for the efficient production of products that will be made in them. Facility engineering is usually carried out by manufacturing engineers with expertise in tools, materials, processes, and the product(s) to be manufactured. (14)

fermentation: A biochemical conversion process that uses microorganisms to decompose a biomass material to create the liquid fuel alcohol. (11)

final project report: The summary of the design process for a specific project. (6)

first law of thermodynamics: An application of the law of conservation of energy, which states that energy cannot be created or destroyed. (15)

fixture: The type of tooling used to guide a work piece. (14)

flammability: The ease at which a material will ignite. (7)

flap: An airplane component that is located on the inside rear of wings and can be adjusted at takeoff and landing for additional lift. (13)

floor joist: A beam that is designed to resist bending as people walk across a floor. (9)

flow process chart: A chart used to record and communicate the order of the processes dictated by the manufacturing engineer to make each part. (14)

fluid dynamics: The study of fluid flow. (15)

fluid flow: Liquids or gases in motion. (15)

fluid motor: A device similar to a fluid pump, only used in reverse. Fluid is pumped through gears to turn the gears and gear shaft. (10)

fluid pump: A pump used by hydraulic systems to compress fluids. (10)

fluorescent lamp: An energy-efficient lamp that uses a long tube coated on the inside with phosphorous and filled with an inert gas. Mercury inside of the tube is ionized, creating ultraviolet light, which causes the phosphorous to glow. (8)

force: The push or pull of an object resulting from contact with another object. (10)

forming: The mechanical process used to change the shape of materials through compression, bending, or stretching. (14)

formula: A series of mathematical symbols that represent a rule or relationship between concepts. (6)

free association: The act of describing as many ideas as possible without any concern about their ability to be accomplished. (3)

free body diagram: A simple drawing that includes three components: the structural members and joints, the supports, and the loads or forces that are applied. (9)

freewriting: An individual brainstorming technique in which an engineer generates possible ideas by writing them down. (3)

friction: A force that acts against motion when two surfaces rub together. (10)

function: The criteria tested on a design to determine whether it works properly. (6)

future process: A brainstorming technique in which engineers intentionally focus on solutions that are not possible yet because of technological or scientific limitations. (3)

G

Garbage Patch: The area of marine trash in the North Pacific Ocean estimated to be about twice the size of Texas and made up mostly of plastic. (15)

gas discharge lamps: A lamp that creates light when gas inside of a globe is ionized and glows. (8)

gasification: The thermochemical conversion process of turning biomass into carbon dioxide and hydrogen through a controlled amount of high temperatures and oxygen. (11)

gas turbine engine: An engine, also known as a jet engine, that pulls air into the front of the engine, increases the pressure of the air, and forces it out the back of the engine at great speed. (13)

gauge pressure: The measurement of pressure relative to the atmospheric pressure. (15)

gear: A device that transmits rotational force against another gear or device. (10)

gear ratio: The relationship between two gears that describes the change in torque. (10)

gene: The hereditary unit of living organisms that contains information about the traits from parents and gives instruction to the rest of the cell on which traits to pass on to the offspring. (11)

generator: A device that produces electricity by changing mechanical energy to electrical energy through the use of magnets. (8)

genetically engineered crop: A plant whose genetic structure has been changed intentionally. (11)

genetics: The field of study focused on the ways in which genes are used inside the cell structure. (11)

geomatics engineering: A type of engineering usually associated with civil engineering, interested in determining the location of objects on the Earth. (9)

geospatial modeling software: The civil engineering software that uses spatial and analytical methods integrated with information about the earth's surface and data about people. (6)

green design: A type of design that focuses on creating products that are not harmful to environment throughout their life cycle. (16)

gyre: The rotating oceanic current. (15)

H

harvesting: The process of retrieving mature natural resources that grow on the earth. In manufacturing, harvesting commonly refers to the cutting of trees for wood and wood products. (14)

herbicides: Chemicals sprayed by farmers to eliminate weeds that may damage a specific crop. (11)

homeostasis: The ability of an organism to regulate itself in order to maintain a constant state. (11)

horsepower: The amount of work a horse can do in one minute, which is 33,000 foot-pounds. (10)

human-computer interaction: The study of the interactions between humans and computers. (12)

hybrid car: A fuel-efficient car that uses an internal combustion engine combined with an electric motor and batteries. (8)

hydraulic system: A system that uses a liquid, such as water or oil, to transmit power. (10)

I

ideation: The process of generating ideas. (2)

incandescent lamp: A device that uses electricity to heat a tungsten filament in a vacuum until it glows and creates light. (8)

inclined plane: A simple machine that uses a flat surface that is higher on one end. (10)

infrared temperature measurement device: A device that measures the thermal radiation emitted from a material. (15)

Institute of Electrical and Electronics Engineers (IEEE): The broadest professional society for electrical engineers, with over 375,000 members in more than 160 countries. (8)

insulator: A material with a very high resistance that does not allow current to flow. (8)

integral balance: A type of balance that is taken at two different points to show what is happening between one point and another. It is typically taken at the beginning and end of a process. (15)

integrated circuit (IC): Consists of multiple electronic circuits etched into a thin layer of silicon and enclosed in a protective material like plastic. (8)

intermittent manufacturing: The type of manufacturing process that produces smaller batches of the same part. (14)

ion: An electrically charged atom. (8)

J

jig: The type of tooling used to guide tools to the correct location. (14)

joint: The device that connects two or more structural members together. (9)

just-in-time (JIT) delivery system: A delivery system that allows for the delivery of parts and materials at exactly the time they are needed in production. JIT delivery cuts down on the costs of maintaining a large inventory, but it is a much more complex system to manage. (14)

K

kinetic energy: Energy in motion. (10)

L

laminar flow: A type of flow that has no disruption between the layers of the moving fluid, with no eddies or changes. (15)

land surveying: The process of taking and using measurements to determine the exact size and shape of a piece of land. (9)

law of conservation of energy: The law that states that energy cannot be created or destroyed. It can only be converted from one form to another. (8)

leader: A line with an arrow on the end pointing to the feature. (5)

lever: A simple machine that uses a stiff bar rested on a fulcrum, or pivot, to lift or move a load. (10)

library research: A type of research that uses different forms of printed and digital materials as a source of information. (4)

lift: The upward force acting on wings when air is moved downward. (13)

light-emitting diode (LED): An extremely efficient lamp that creates light by forward biasing semiconductor material. (8)

linear motion: Movement in a straight line. (10)

liquid column gauge: A type of gauge that measures pressure using fluid in a tube. One end is connected to the pressure to be measured, and the other is exposed to a control pressure, which could be atmospheric pressure or a vacuum. (15)

load: The forces the structure must withstand. (9)

location dimension: A type of dimension that shows the distance between two different features. (5)

logic: The system of operations performed by a computer. (12)

M

management engineer: An engineer who coordinates all of the engineering processes including materials and human resources. (16)

manufacturability: The ease at which the material can be transformed from raw material to a usable material. (7)

manufacturing: The process of changing raw materials to make them more useful. (14)

manufacturing engineering: The design of machines, tools, and processes used to manufacture goods. (1, 14)

mass balance: A property founded in the law of the conservation of matter, which states that matter cannot be created or destroyed and, therefore, must be constant in a closed loop. (15)

mass flowmeter: A type of flowmeter that measures the mass rather than the volume. (15)

material safety data sheets (MSDS): An information sheet that includes a chemical's common name and chemical name, hazard warnings, and the manufacturer's name and address. (15)

materials engineering: The understanding and modification of the structure and properties of materials to improve the performance and processing of the material. (1, 7)

materials handling: The movement of materials and products through a plant. (14)

mathematical model: A type of model used to find solutions to problems using mathematical prediction. (6)

mechanical advantage: The number of times a machine or tool multiplies the input force to move a load. (10)

mechanical drawing: A highly accurate technical drawing meant to communicate the size and shape of objects in great detail. (2)

mechanical energy: Energy in motion that uses mechanical devices for conversion. (10)

mechanical engineering: The designing, building, and maintaining of mechanical and fluid systems. (1, 10)

mechanical flowmeter: A type of flowmeter that uses a variety of mechanical devices inside of a pipe to measure flow. (15)

mechanics: The study forces and motion on physical objects. (9)

melting point: The temperature at which the material changes from a solid to a liquid. (7)

metal: A chemical element that belongs to one of the families of metals on the periodic table; a type of inorganic material with good conductivity to heat and electricity. (7, 14)

mining: The process used to extract materials like metals, coal, uranium, iron, diamonds, and stone from beneath the surface of the earth. (14)

mock-up: A physical model used to show the design of an object. (6)

monoclonal antibodies: Antibodies that work like natural antibodies in the body by finding the unwanted germ and attacking, to which treatments or medicines can be attached. (11)

motor: A device that uses magnetism to change electrical energy to mechanical energy. (8)

multiview drawing: A drawing with true shape that shows what a part will look like from a given direction. See also *orthographic drawing*. (2)

N

NAND gate: A gate that is a combination of a NOT and an AND gate. If either or both inputs are 1, then the output is 0. (12)

nanoparticle: The most basic component at the nanoscale. (7)

nanotechnology: The design of new materials and devices at the scale of a nanometer. (7)

nanotubes: Nano-sized cylinders of carbon. (7)

nanowire: A small strand of material that ranges 1 nm–60 nm in width. (7)

natural selection: The ability of living organisms to adapt to their environment through the natural change of characteristics that are needed to help the organism survive. (11)

negative impact: The costs or effects that cause damage to people or the environment. (16)

neutron: A subatomic particle with a neutral charge. (8)

Newton's third law of motion: The law that states that for every action there is an equal and opposite reaction. (13)

nondestructive material test: A test that leaves the material intact and does not destroy the material. (7)

NOR gate: A gate that is a combination of an OR and a NOT gate. If both inputs are 0, the output is 1. If either or both inputs are 1, then the output is 0. (12)

NOT gate: A gate that is also called an inverter because it changes the input. If the input is 1, then the output is 0. If the input is 0, then the output is 1. (12)

O

oblique drawing: A type of pictorial drawing that features one side of the object as the front image. (5)

Occupational Safety and Health Administration (OSHA): An agency of the US Department of Labor, whose mission is to ensure safe and healthful working conditions for all workers. (15)

ohm (Ω): The base unit of measurement of resistance. (8)

ohmmeter: A meter that is used to measure resistance. (8)

Ohm's law: The law that defines the relationship between voltage, current, and resistance. (8)

open-channel flowmeter: A type of flowmeter that measures the flow in a channel rather than in a pipe. (15)

operation process chart: A type of chart used to study all operations in the manufacture of an entire product. (14)

operations engineer: An engineer who controls and maintains large systems, such as manufacturing facilities, railroad systems, and traffic systems. (16)

operation sheet: The way the operation name, machine, and tooling are recorded and communicated. (14)

optimization: The process of creating the most optimal solution within the specifications and constraints. (1)

oral presentation: The spoken delivery of a report to an audience. (6)

OR gate: A gate that provides an output of 1 if either or both of the inputs are 1. (12)

orthographic drawing: A drawing with true shape that shows what a part will look like from a given direction. See also *multiview drawing*. (2)

oscilloscope: An electrical test device whose screen can show the exact shape of a wave and, therefore, any possible distortion. It can measure voltage, frequency, pulses, and the timing of multiple signals. (8)

P

parallel circuits: Circuits that have more than one load and multiple paths for current flow. (8)

Pascal's law: The law that states that all fluids exert the same amount of pressure in all directions when in a limited space. (10)

patent: An exclusive right that is granted by a government to the creator of a new product or design so others cannot produce it without permission. (16)

perspective drawing: A type of pictorial drawing that shows an object from a specific point of view and simulates what the eye sees. (5)

pictorial drawing: A drawing that shows a single view of an object in a way that makes it look 3-D as your eye would see it. (2)

piers: The main vertical columns that transfer the load of the bridge into the ground. (9)

piping and instrumentation diagram: A detailed type of plan diagram that shows every detail of plant layout and design, including all chemical flows, instrumentation, temperature, control systems, location of all equipment, and everything else needed to build and maintain the facility. (15)

pitch: The up-and-down movement of the nose and tail. (13)

plant layout: The arrangement of facilities whose design is based on the location of the materials that will be made into products and how they are moved through the plant, equipment layout, utility location, and traffic flow. Layout is also based on the economics of construction and operation, the specific requirements of the processes that will take place, the convenience of the maintenance that will be necessary, possible future expansion, and safety. (14, 15)

plasticity: The deformation that occurs from the yield point to the fracture point. (7)

pneumatic system: A system that uses air instead of fluid to transmit power. (10)

polarity: The positive or negative condition at the power supply terminal. (8)

polymer: An organic material made up of a long chain of small molecules (primarily made up of carbon and hydrogen atoms) that form a much larger molecule. (7, 14)
positive impact: The benefits or successful solutions to engineering design problems. (16)
potential energy: Energy that is stored and waiting to be used. (10)
power: The rate at which work is done or the amount of work done based on a period of time. (8)
power system: A system that takes energy and converts it into power to accomplish work. (10)
predictive analysis: A tool using many different factors, including statistics and theoretical models, to predict future events. (6)
pressure: A measurement that is force per unit area. (15)
primary cell: A disposable cell. (8)
primary processing: The processing of raw materials into standard stock. (14)
problem: An unknown quantity or something that needs to be changed in a situation. (3)
problem statement: A statement that outlines the problem in clear terms but is not so specific that it limits creativity in design. (2)
process flow diagram: A detailed diagram that includes main flow of chemicals, general processes, and main equipment. (15)
process layout: The layout based on the location of the equipment depending on the process it performs. (14)
product layout: The layout based on the entire facility being designed around the manufacture of one product. It is commonly used for continuous manufacturing. (14)
production engineer: An engineer who plans, coordinates, and schedules the manufacturing of consumer goods. (16)
Professional Engineer (P.E.): The designation for engineers who have completed licensure requirements, allowing engineers to approve, sign, and stamp plans and documents. (16)
propeller: The rotating blades that force air toward the rear of an aircraft causing the aircraft to move forward. (13)
propulsion system: The system that creates thrust for movement. (13)
proton: A subatomic particle with a positive charge. (8)
prototype: A physical model of a final product or some aspect of a product. (2)
pulley: A simple machine that consists of a wheel and rope used to move objects. (10)
pyrolysis: The thermochemical conversion process that involves breaking down biological materials with heat and reduced oxygen. (11)

Q

quality control: The system whereby manufacturers ensure the quality of their products meets or exceeds expectations. (14)

R

radiography test: A test that uses x-rays that pass through the material. (7)
rapid prototyping: A way of creating 3-D models that uses machines and builds by laying down many thin layers of material until the entire shape has been created. (2)
raw materials: Natural resources found in the earth, on the earth, and in the seas. The materials are then made into industrial materials. (14)
reciprocating motion: Linear back-and-forth motion. (10)
refined sketch: A type of sketch that combines all the components of the final design, which may be a combination of different ideas. (4)
rendering: A full-color drawing that shows what the object will look like in a given light. (2)
research: A scientific way to discover facts about a certain topic or situation. (4)
research engineer: An engineer who works with scientists to find uses of scientific discoveries. (16)
resistance: The opposition to current flow. (8)
resistance temperature measurement device: A measurement device that relies on the concept that resistance, or conductivity of a conductor changes as temperature changes. (15)
resistivity: The measurement of how well a material resists the flow of electricity. (7)

resistor: An electrical component used to limit current flow and divide voltage. (8)
resistor color code: A system of using color bands on resistors to indicate resistance rating and tolerance. (8)
reverse engineering: A method of determining the properties or function of a device by taking it apart and looking at its operation structure. (6)
"right to know" laws: Laws that are designed to ensure people know what chemicals they are being exposed to and what the health effects could be. Employees have a right to know what chemicals they are using at work. Community members who live near plants using hazardous chemicals have a right to know what chemicals they are exposed to. (15)
risk analysis: A process that identifies and evaluates as many of the potential impacts of an engineered solution as possible. (16)
roadway: The horizontal structure that enables transportation across the bridge. (9)
robot: An automatically controlled, reprogrammable, multipurpose machine. (12)
rotary actuator: A device that can provide a small amount of rotation. (10)
rotary motion: Motion that moves in a circle. (10)
rough sketch: The first drawings completed by engineers, of solutions that are in the early stages of development. (4)
rudder: The control surface located on the rear of the vertical stabilizer, used to control side-to-side movement of the nose. (13)

S

sales engineer: An engineer who works with clients to find products that meet their needs. (16)
satellite: A type of spacecraft that orbits the Earth because the centrifugal force created by its motion is in perfect balance with the Earth's gravitational pull. (13)
schematic diagram: A basic sketch of circuitry showing schematic symbols for parts and lines to represent conductors. (8)
schematic drawing: A type of working drawing used to show how different parts are connected together to form a system. (5)
schematic symbols: Simple symbols used to represent electrical parts. (8)
screw: A simple machine that is an inclined plane wrapped around a cylinder. (10)
second law of thermodynamics: The law often called the entropy law, concerned with the idea that concentrated sources of energy will naturally disperse. (15)
secondary cell: A cell that can be recharged. (8)
secondary processing: The processing of stock materials into useful products. (14)
selecting and sequencing manufacturing operations: The decisions of what operations, or processes, will be used to create the product and in what order, or sequence, they will be performed. (14)
semiconductor: A material with conductive capabilities between that of conductors and insulators. Silicon is the most common semiconductor. (8)
sensor: A component that creates an electrical signal based on environmental conditions. A sensor can be used to monitor things like temperature and light. (8)
separating: The process of cutting materials to the desired size or shape through mechanical, heat, or chemical means. (14)
series circuits: Circuits with only one path for current to flow from the power source through the circuit and back to the power source. (8)
series-parallel combination circuits: Circuits with characteristics of both series and parallel circuits. (8)
shaft: A cylindrical piece used to transfer rotary motion. (10)
shape dimension: A type of dimension used to provide detailed information about the shape of features. (5)
shear: A force that acts in opposite directions across a material. (9)
shear stress: A bending or twisting force, like the stress that occurs when using a wrench. (7)

simple machine: A tool that makes work easier, including the lever, inclined plane, wheel and axle, screw, wedge, and pulley. (10)

site layout: The description of the specific location of all required facilities, such as the plant itself, roads, parking, storm water management, and utilities. (15)

size dimension: A type of dimension that describes the length, width, and depth of an object. (5)

sketch: A simple drawing used in the idea generation stage in order to record and communicate ideas so they can be refined further in the solution creation step. (2)

societal impact: The effects that engineered products have on the lives of groups of people, such as housing, safety, food, communication, and transportation. (16)

Society for Manufacturing Engineers (SME): The largest professional society for manufacturing engineers with over 500,000 members in more than 70 countries. (14)

software engineering: The application of engineering principles to software design. It is a systematic, quantifiable approach to software development. (12)

solar cell: A cell that uses light to produce electricity. (8)

solderless breadboard: A platform ideal for experimentation and testing circuits before they are constructed. Components and leads can easily be moved from one place to another because no soldering is required to make connections. (8)

specifications: The design requirements of an engineered solution. (1)

specification sheets: Provide necessary technical information to the builder or manufacturer of a product, and include materials, how the product is to be made, and tolerances. (2)

specific constraints: The conditions that are directly related to the engineering design problem at hand. (3)

static electricity: The excess of charge on the surface of an object. (8)

static load: The weight of the structure itself (known as dead load) and weight added to the structure under normal use (known as live load). (9)

statics: The study that deals with the analysis of loads on objects at rest (or in equilibrium). (9)

strain: The deformation that occurs from stress. (7)

stress: The amount of force or load that is applied to a material. (7)

structural analysis: The analysis focused on ensuring the structure is as efficient as possible. (9)

structural frame: The columns and beams used to build a structure, called a skeleton. (9)

structure: An arrangement of parts built to remain stable while withstanding forces. (8)

struts: Braces that resist compression. (9)

surface tension: A characteristic almost like a film on the surface, caused by the molecules of a liquid tending to be more attracted to each other than they are to their surrounding materials. (15)

suspension bridge: The world's longest bridges, which utilize tension forces. (9)

switch: An electrical device used to open and close circuits or redirect current from one circuit to another. (8)

T

tensile strength: The ability of a material to withstand a force that pulls the material apart. (7)

tension: A pulling force that tends to stretch a material. (9)

thermal conductivity: A material property determined by how well heat is transferred through the material. (7)

thermal resistance: The reciprocal of thermal conductivity. (7)

thermochemical conversion: The bioconversion process that uses heat to create a chemical change in biological material. (11)

thermocouple sensors: Temperature sensors that are made from two different pieces of conductive material. As the temperature of the thermocouple increases, it creates a voltage. This voltage can be measured to determine the temperature. (15)

thermodynamics: The study of work, energy, and efficiency in large-scale systems. (15)

thermoplastic: A type of plastic that can be easily reheated and reshaped with little or no damage to the plastic because there is little or no bonding between the chains. (14)

thermoset plastic: A type of plastic that is generally stronger than thermoplastic because it is cured with heat and pressure to crosslink the chains. Once they have been cured, it can no longer be reshaped and will remain rigid even when heat is applied. (14)

three-dimensional (3-D) model: A type of model that can be made out of products like clay, plastic, wood, and foam, or can be drawn using 3-D CAD software. (2)

thrust: The forward force acting on an aircraft or spacecraft created by air or gasses being pushed to the rear. (13)

thumbnail sketch: See *rough sketch*. (4)

ties: Braces that resist tension. (9)

torque: The measure of how much force acting on an object causes that object to rotate. (10)

torsion: A turning force that is applied to a material or structure. (9)

total robotic station: Tracks the survey rod and calculates the distance and angle without the need of the surveyor standing at the station. (9)

total station: A surveying instrument designed to measure both distance and angles. (9)

trade-off: Something an engineer gives up in order to meet specifications while staying within the constraints; the consideration that gaining one positive quality in a design means you lose one other quality. (1, 4)

tradespeople: Workers who create the design products. (1)

transistor: A device used as a solid state switch or amplifier. (8)

troubleshoot: To systematically search for the cause of a failure. (8)

truss: A structural element used in a number of civil engineering structures, as supports for roofs and floors to bridges. (9)

truss bridge: A type of bridge that uses a truss, which allows for the load to be spread out through all of the structural members in the truss. (9)

turbulent flow: A chaotic or abnormal flow consisting of swirls, or eddies. (15)

U

ultrasonic test: A test that uses sound waves that "bounce off" changes in the material to determine the internal composition of a material. (7)

United States Army Corps of Engineers: The largest employer of civil, structural, and architectural engineers, as well as land surveyors. This organization is responsible for building military and civil works throughout the United States and the world. (9)

V

valence shell: An atom's outer ring of electrons. (8)

valve: A device used to control either the rate or direction of the fluid flow. (10)

variable resistor: A resistor whose resistance can be changed, usually by rotating a knob or sliding a switch. (8)

velocity flowmeter: A type of flowmeter that measures the speed of passing fluid and the depth of the fluid. (15)

viscosity: The thickness of a liquid, or its resistance to being deformed. (15)

volt: The base unit of voltage. (8)

voltage: The amount of pressure behind the flow of electrons. (8)

voltmeter: A meter that is used to measure voltage. (8)

volt-ohm-milliammeter (VOM): A meter that is used to measure voltage, current, and resistance. (8)

W

waste: A by-product of chemical operations. Some waste materials can be reused in the plant or sold to other companies. Waste that cannot be reused or sold must be disposed of in compliance with local regulations. (15)

watt: A unit of electrical power. (8)

Watt's law: The law that states that power equals effort multiplied by rate. (8)

wedge: A simple machine that is a combination of two inclined planes. (10)

wheel and axle: A simple machine that uses a circular wheel with an axle in the middle to create a mechanical advantage. (10)

wind turbine: A type of windmill used to generate electricity from wind energy. (13)

work: The application of force to move an object a distance. (10)

working drawing: A type of engineering drawing that shows the most complete drawing produced. (5)

X

XNOR gate: A gate that is an exclusive NOR gate. XNOR gates provide an output of 1 if the inputs are both 1 or both 0, but not if one is 0 and one is 1. (12)

XOR gate: A gate that is an exclusive OR gate. XOR gates only provide an output of 1 if one input is 1, but not if both are 1. (12)

Y

yaw: The side-to-side movement of the nose and tail of an aircraft. (13)

Z

zener diode: A diode that can conduct in reverse bias and is commonly used in voltage regulation. (8)

Zeroth Law: An observation dealing with thermodynamic equilibrium. (15)

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Engineering Fundamentals

Features

Engineering Fundamentals provides instruction and real-world examples to teach basic engineering concepts, theory, and principles; as well as introduces and describes the most common engineering fields. Students learn engineering solutions are the result of thoughtfully following specific steps or processes, rather than resulting from a trial-and-error method of discovery. The following six features are incorporated to expand the chapter content:

- **Science** features review basic science concepts.
- **Math** features give students a review of basic math concepts.
- **Going Green** features discuss how engineers are striving to make their designs more environmentally friendly.
- **History** features further explore engineers and their designs throughout history.
- **Tools** features detail the types of tools that are used in a particular area of engineering.
- **Design** features explain particular element of the engineering design process.

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